Surveying the Accelerating Universe with Supernovae

Saurabh W. Jha

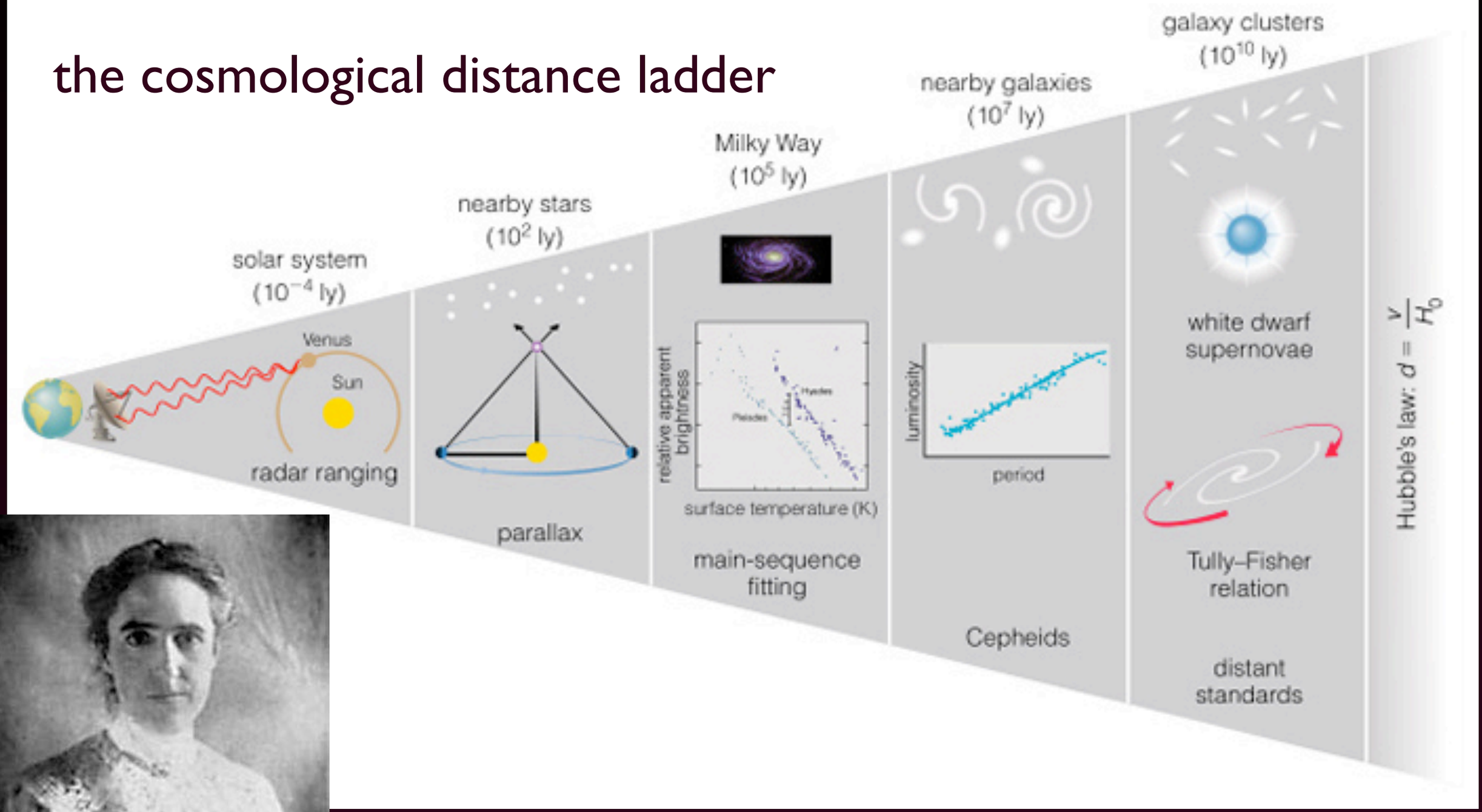
Georgia Tech School of Physics Colloquium March 5, 2012

HST color composite of SN 2008A in NGC 634 from McCully et al. (in prep.)

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

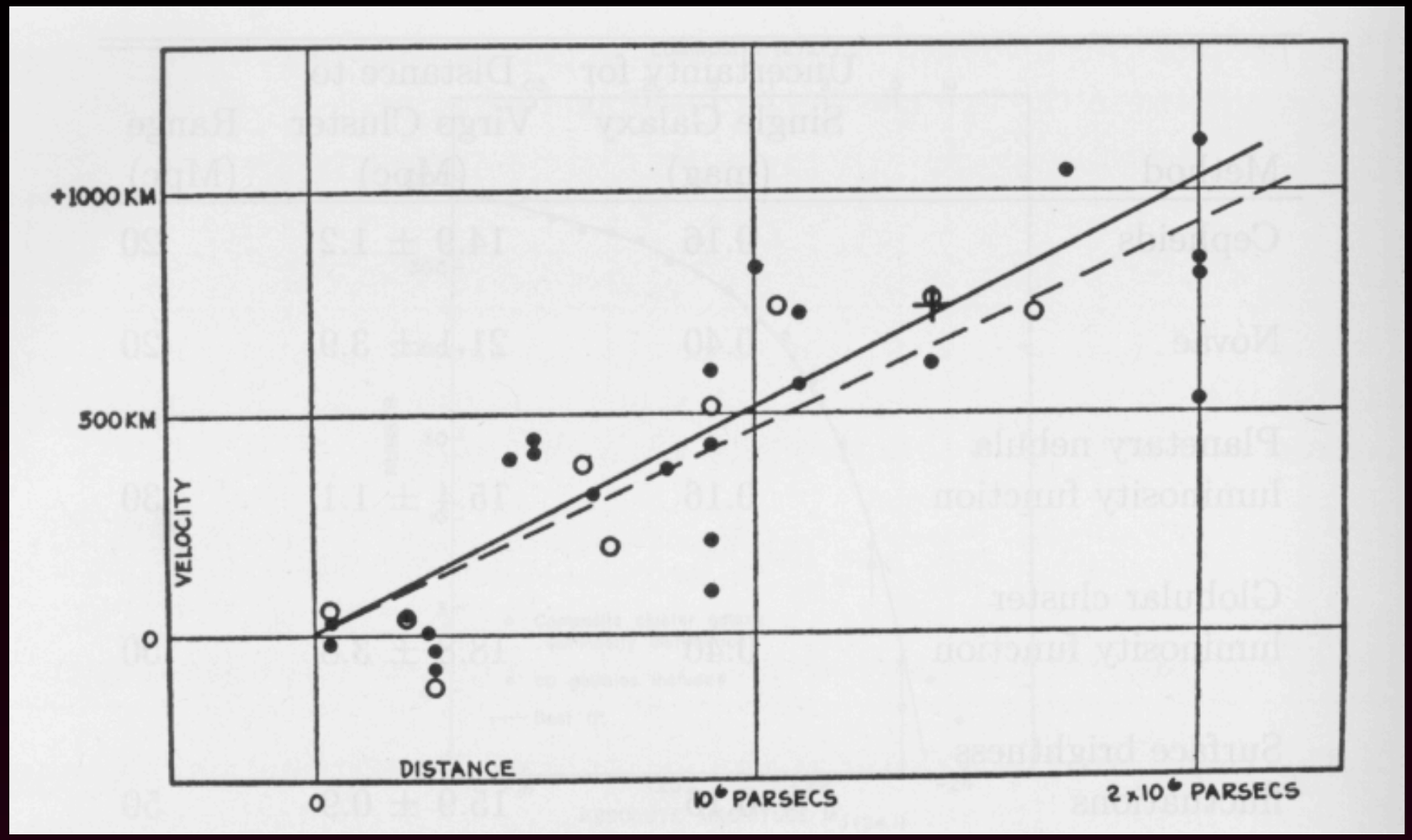
"Surveying" the Universe: Measuring Astronomical Distances

the cosmological distance ladder



Leavitt (1912): 100th anniversary! Cepheid variable stars yield precise distances

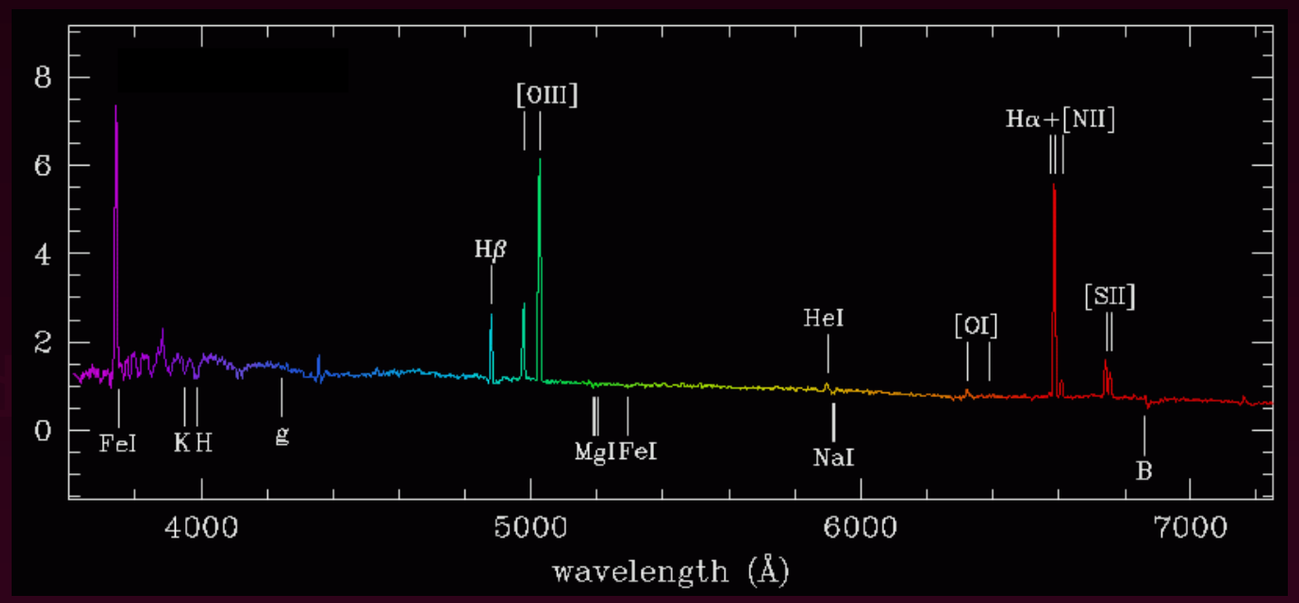
Hubble's Law



Hubble (1929)

measured distances using bright stars in other galaxies and average galaxy properties

measured galaxy redshifts with spectroscopy, using the Doppler shift of atomic spectral lines



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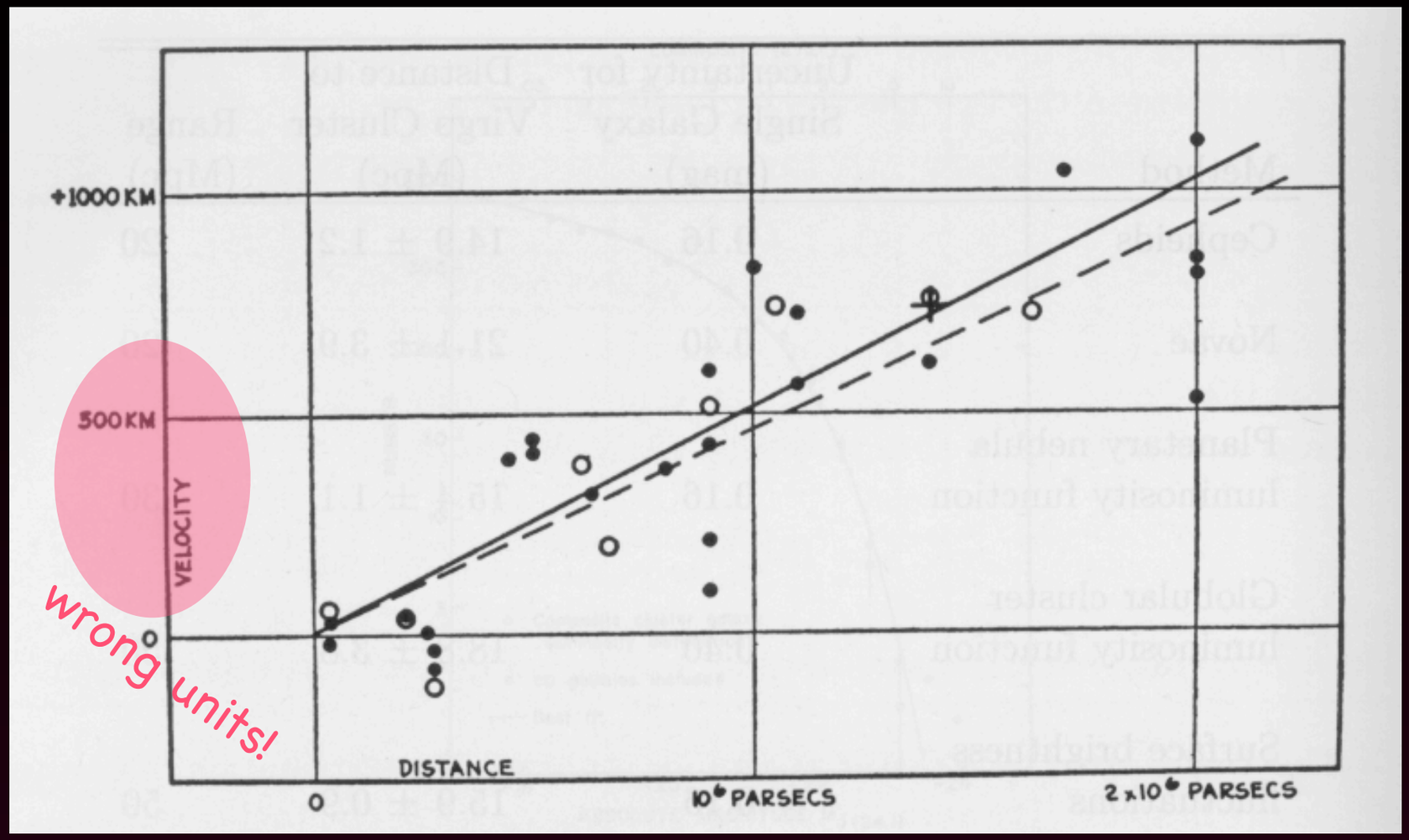

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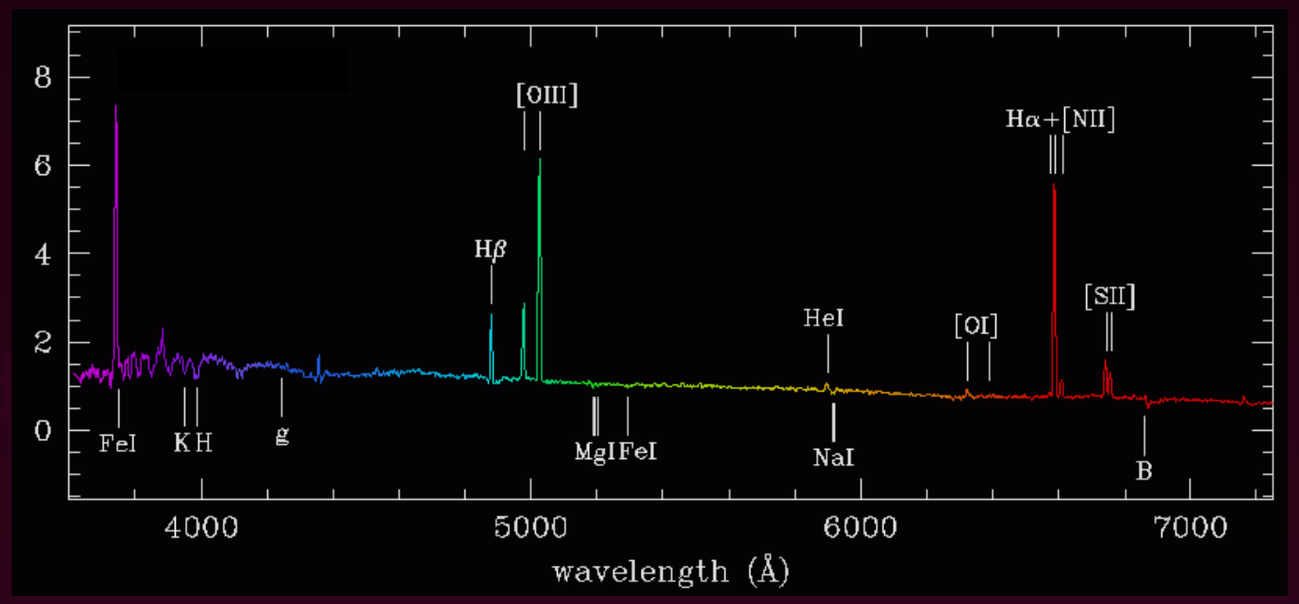

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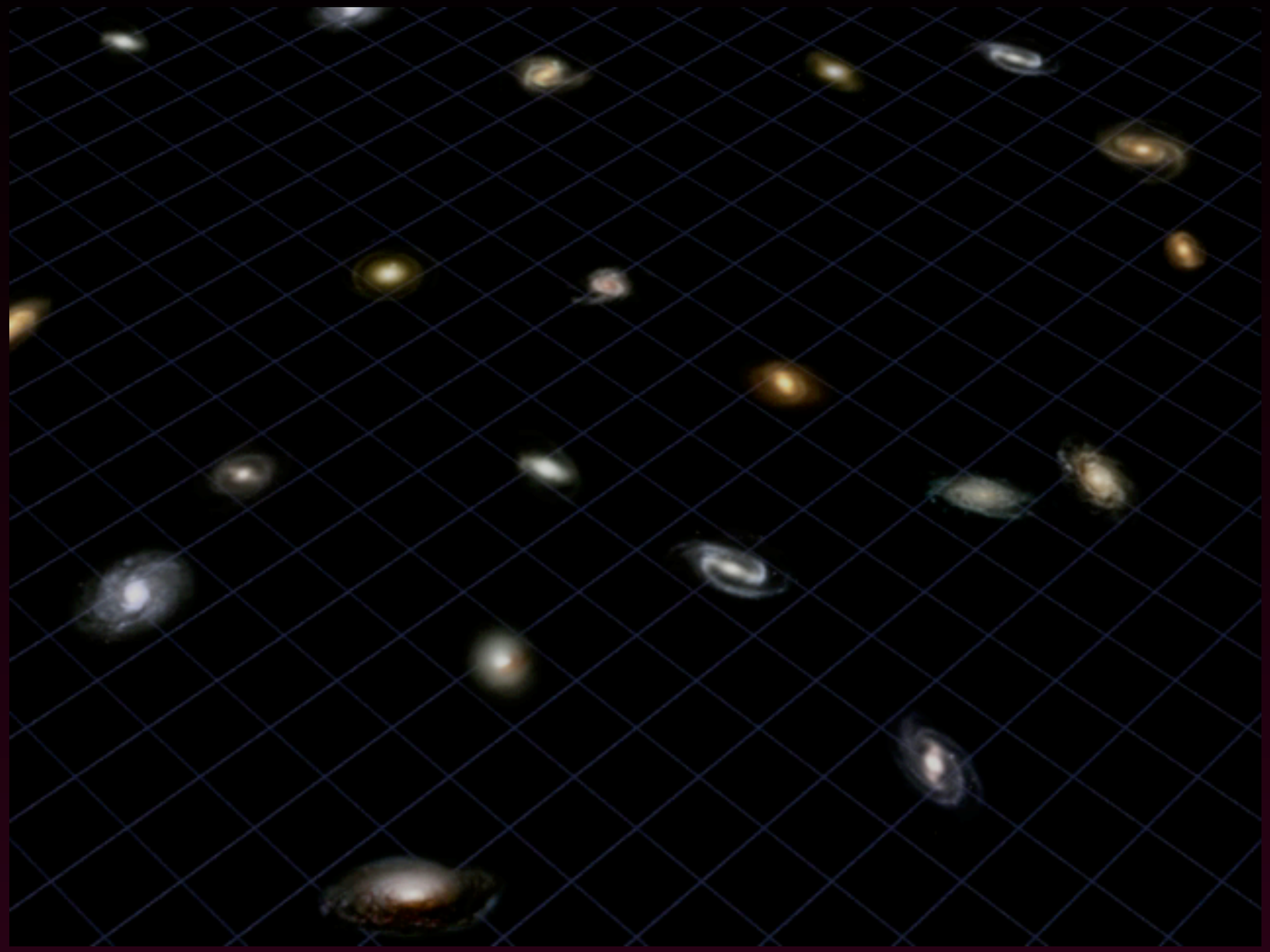
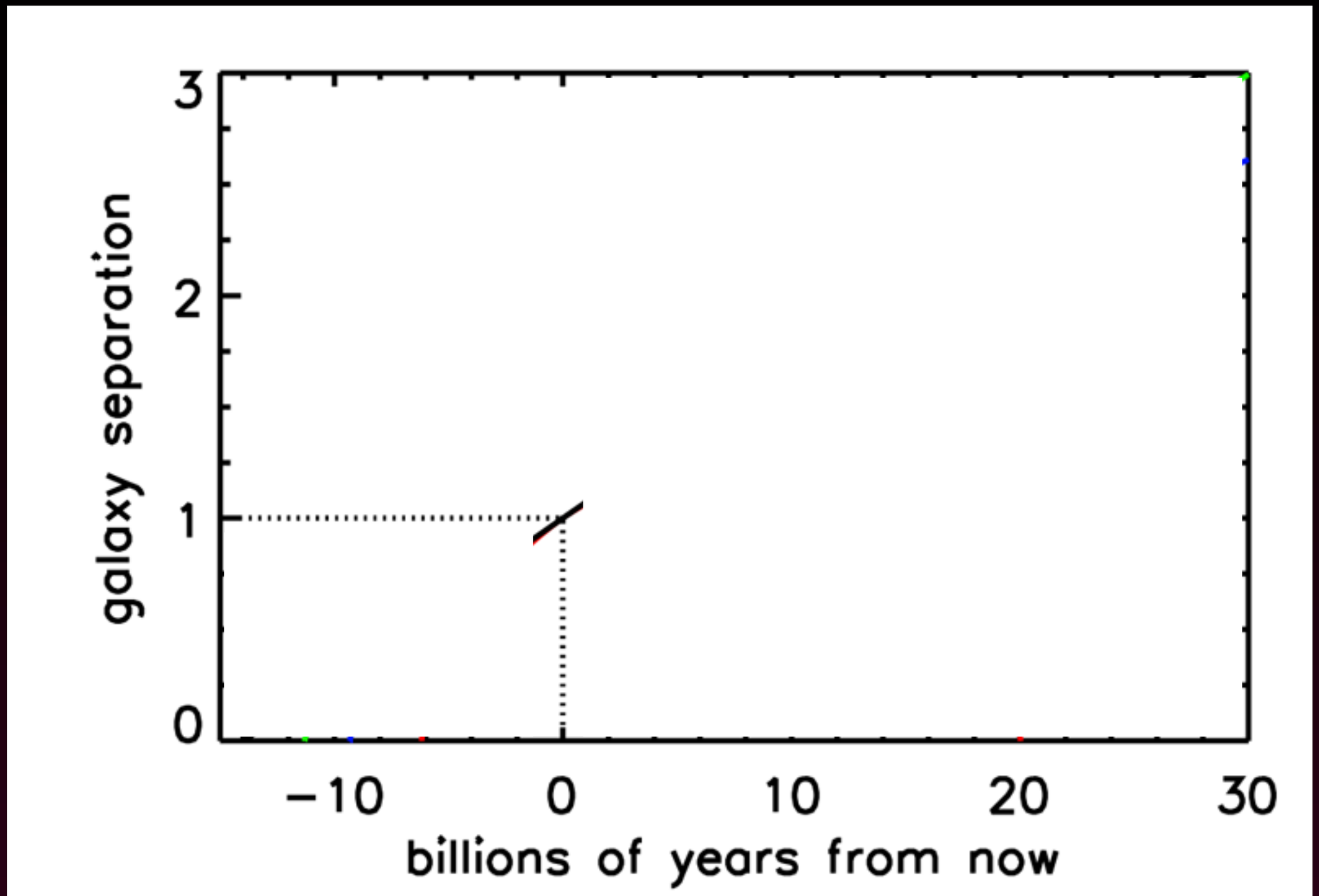


Hubble's Law is a consequence of the expansion of the Universe

$$v = H_0 d$$

History and Future of the Expansion



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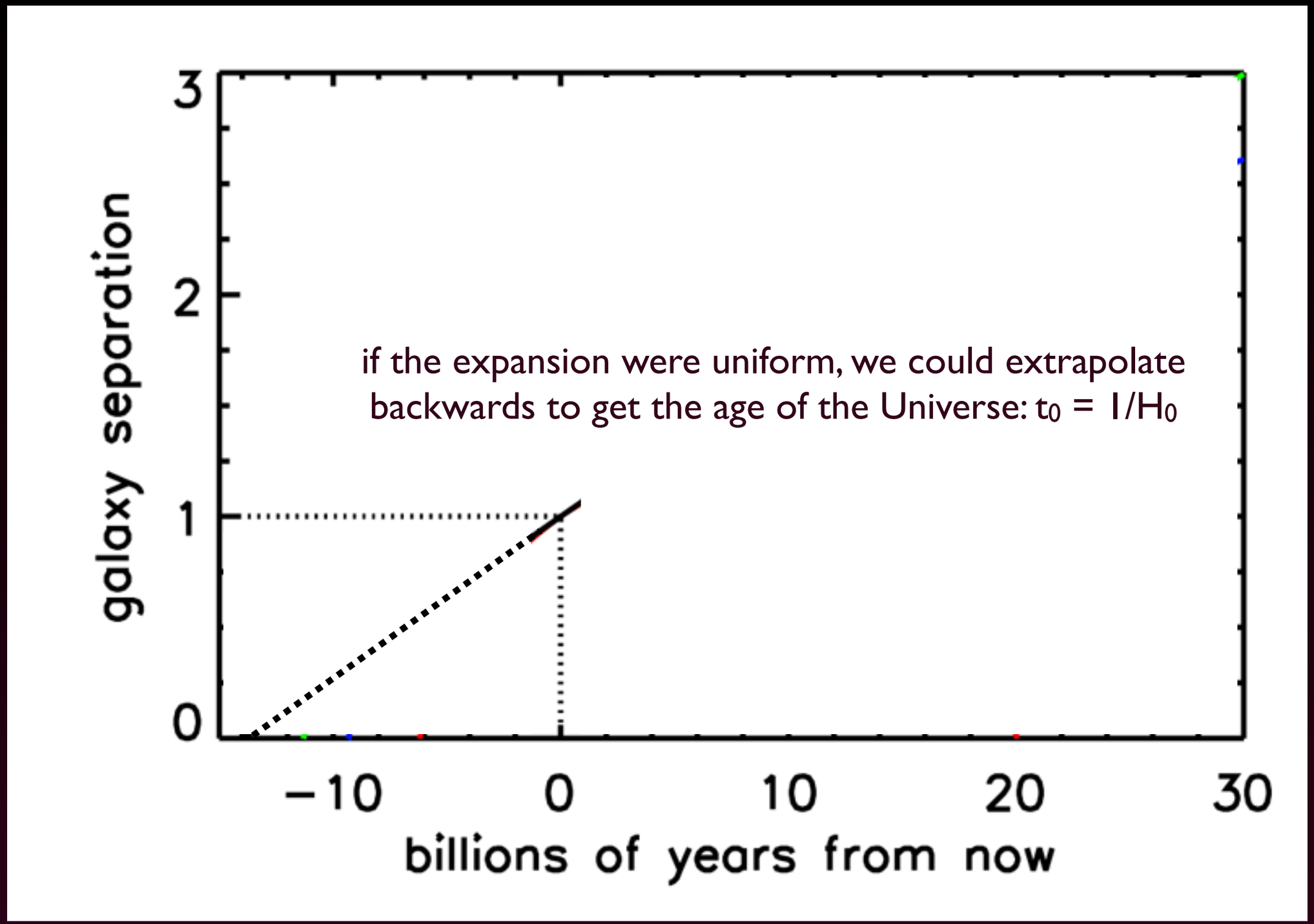

FLRW Cosmography

general relativity + cosmological principle (homogeneity, isotropy)

$$ds^2 = c^2\,dt^2 - a(t)^2\left[\frac{dr^2}{1-kr^2} + r^2\,d\theta^2 + r^2\sin^2\theta\,d\phi^2\right]$$

$a(t) \equiv$ scale factor $\qquad$ k describes spatial curvature

photons: $ds^2 = 0 \quad \Rightarrow \quad \dfrac{a}{a_0} = \dfrac{\lambda_{\rm em}}{\lambda_{\rm obs}} = \dfrac{1}{1+z}$

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kinematic description of scale factor evolution

$$H \equiv \frac{\dot{a}}{a} \qquad q \equiv -\frac{\ddot{a}a}{\dot{a}^2} \qquad \ldots$$

Taylor expand a(t) around t_0: H_0, q_0, j_0, s_0, ...

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$$f = \frac{L}{4\pi d_L^2}$$

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measured flux $f = \dfrac{L}{4\pi d_L^2}$ intrinsic luminosity

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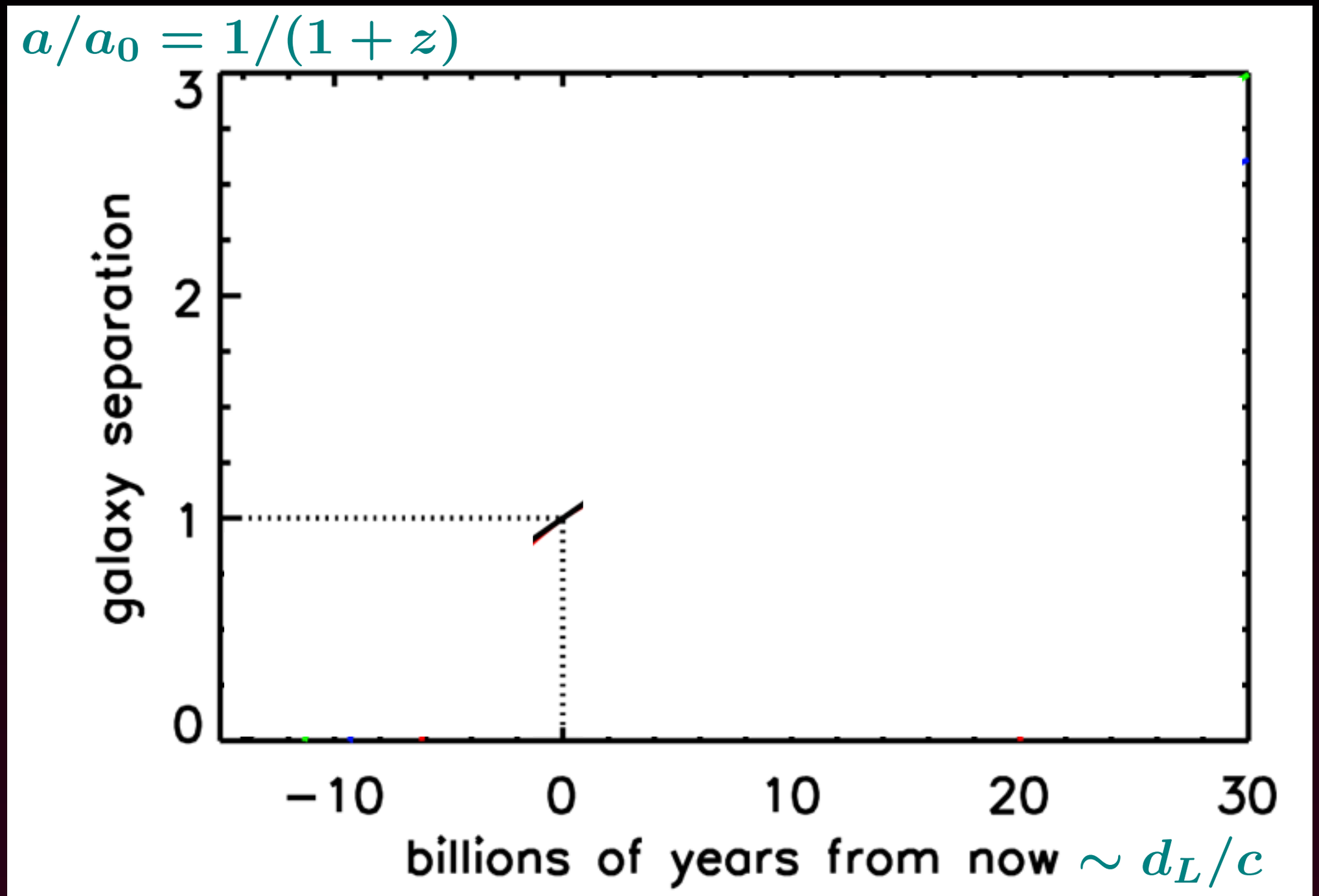
measured flux / intrinsic luminosity

$$f = \frac{L}{4\pi d_L^2} \qquad d_L(z) = c(1+z)\int_0^z \frac{du}{H(u)} \quad (k=0)$$

History and Future of the Expansion



FLRW Cosmography

connecting kinematics and dynamics

a Universe full of perfect fluids, with equations of state:

$P_i = w_i \rho_i c^2 \qquad w \equiv$ equation of state parameter

$$\left(\frac{\dot{a}}{a}\right)^2 \propto \rho_i \qquad \rho_i \propto (1+z)^{3(1+w_i)}$$

$$\frac{\ddot{a}}{a} \propto -(\rho_i + 3P_i/c^2) = -\rho_i(1+3w_i)$$

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	w	density	acceleration	a(t)
matter (normal/dark)	0	$\rho_M \propto (1+z)^3$	$\propto -\rho_M$	$\propto t^{2/3}$
radiation	+⅓	$\rho_R \propto (1+z)^4$	$\propto -2\rho_R$	$\propto t^{1/2}$
cosmological constant	−1	$\rho_\Lambda = \text{const}$	$\propto +2\rho_\Lambda$	$\propto e^{Ht}$

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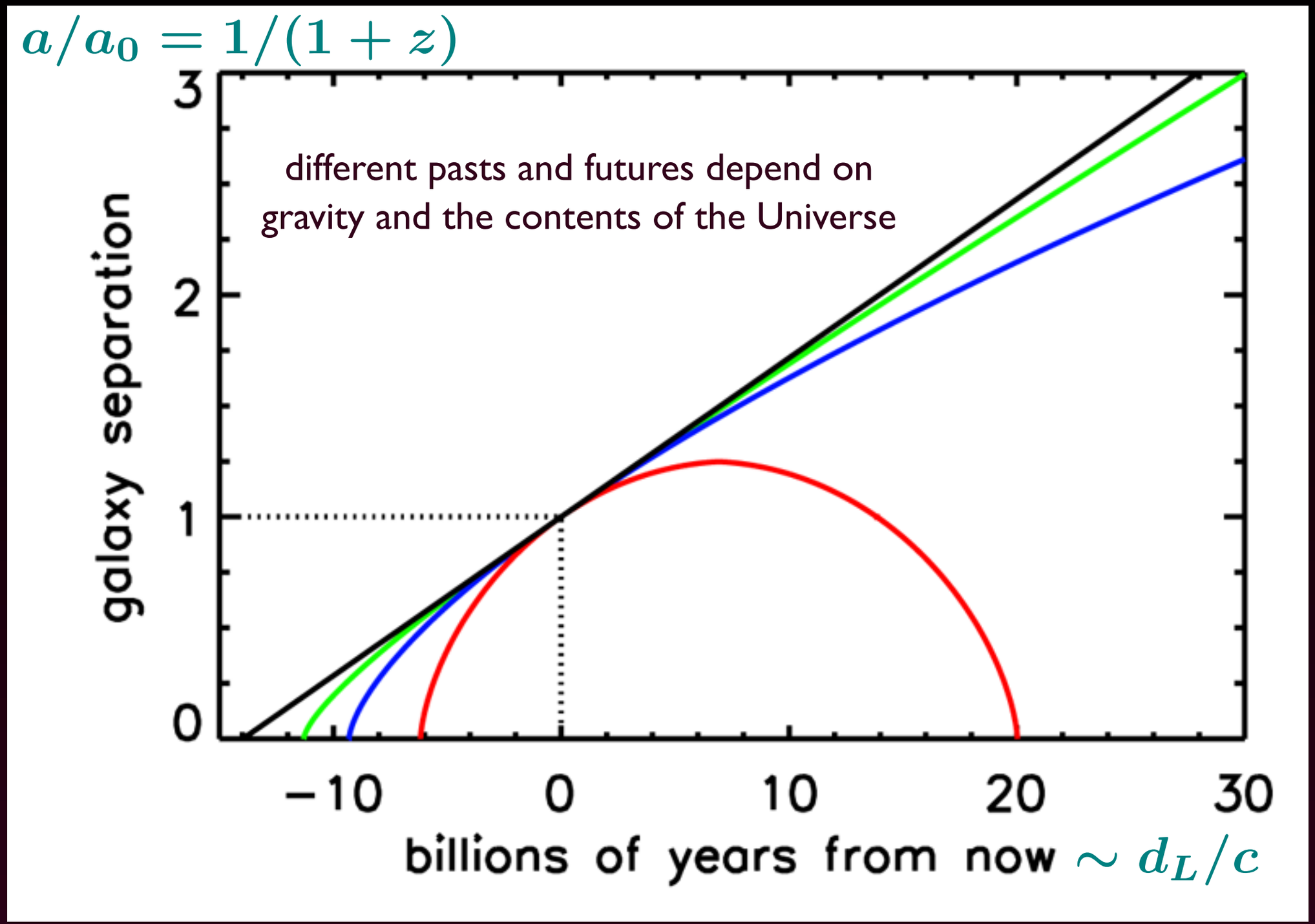

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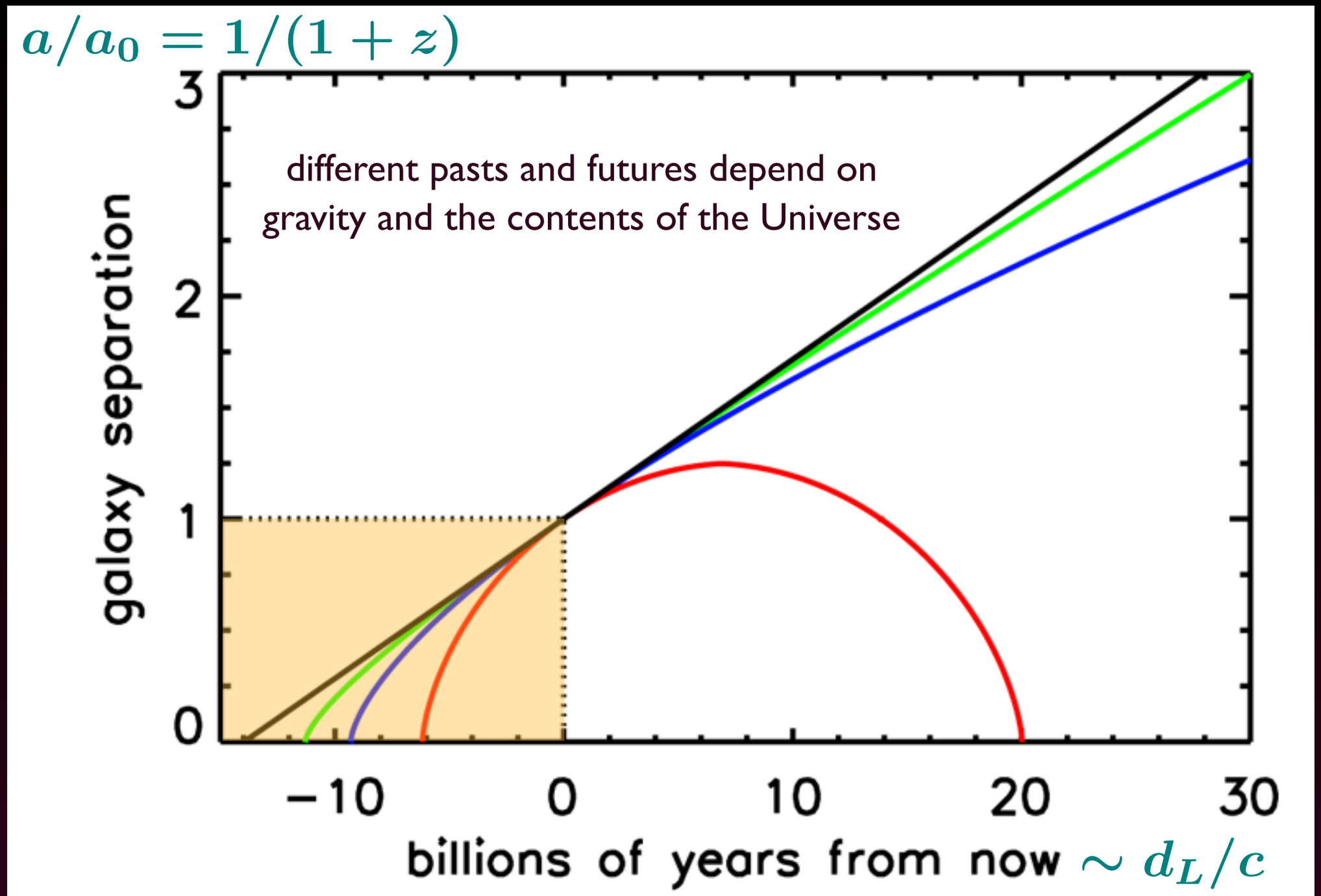


redshift yields the cosmic scale factor

distance tells the time, but we need a good distance indicator

Type Ia SN 1998bu in M96

March 14, 1997

Type Ia SN 1998bu in M96

March 14, 1997

May 18, 1998

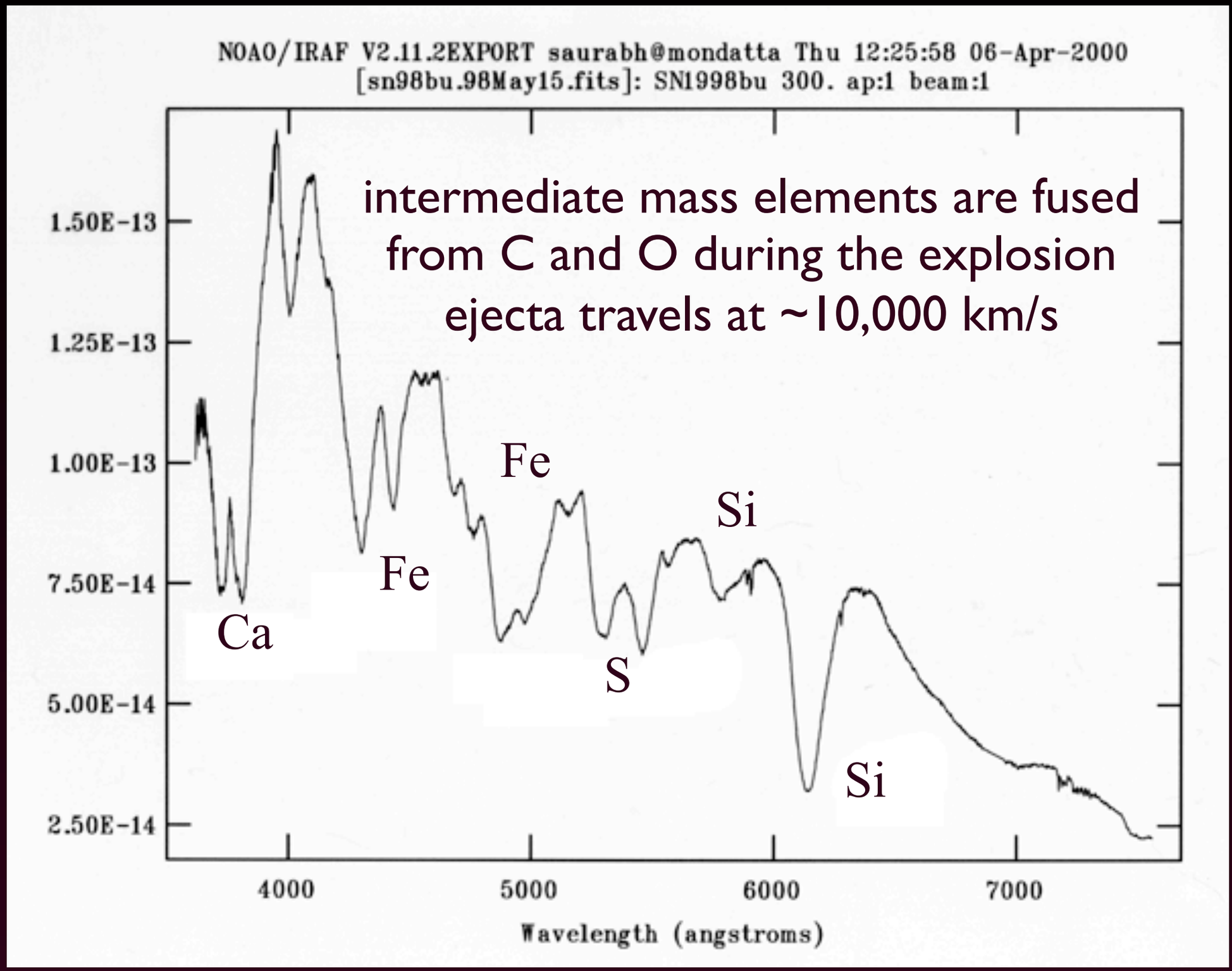
Type Ia SN 1998bu in M96

March 14, 1997

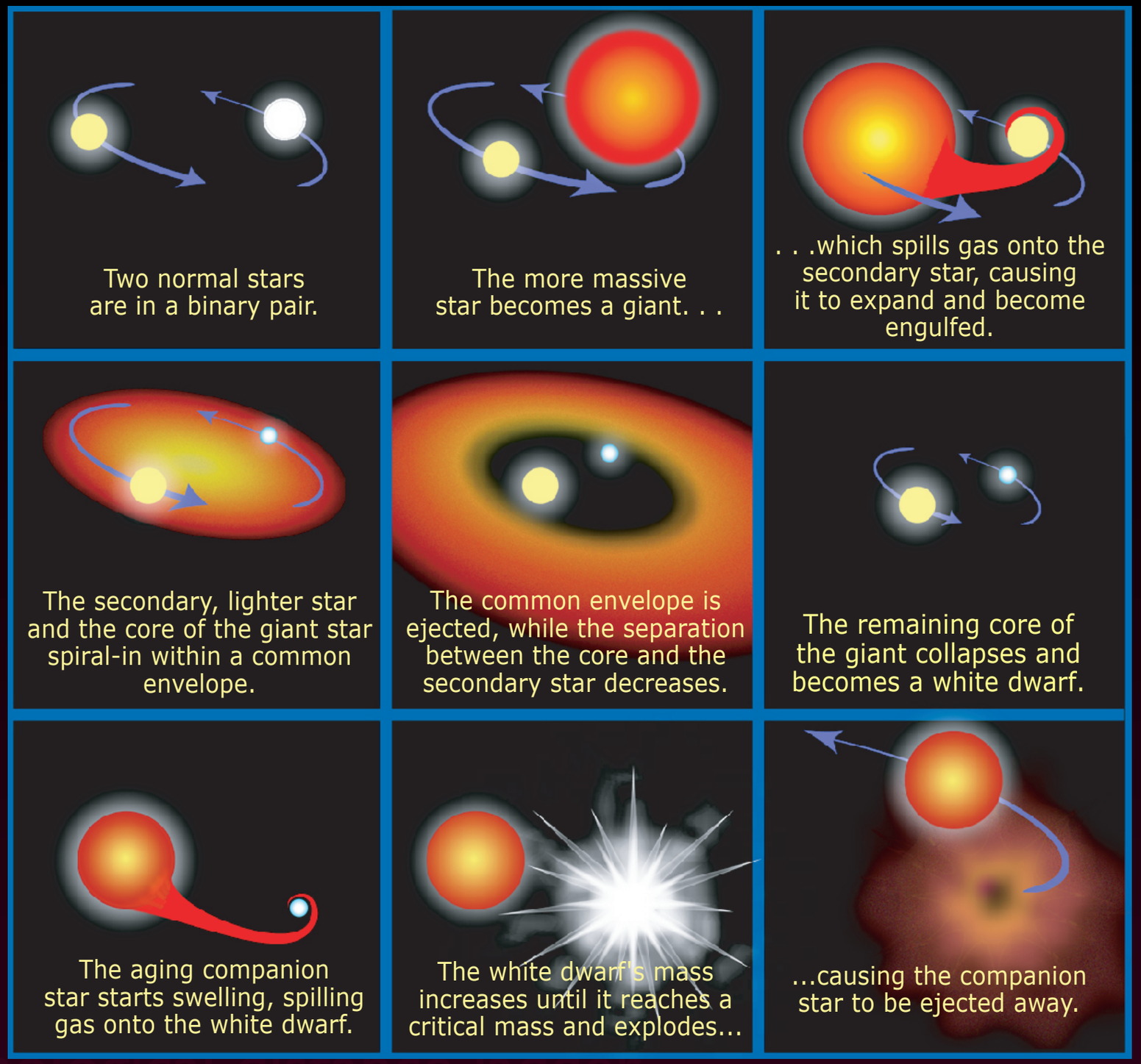
one star in this galaxy becomes as bright as 10 billion stars!

May 18, 1998

SN 1998bu maximum light spectrum

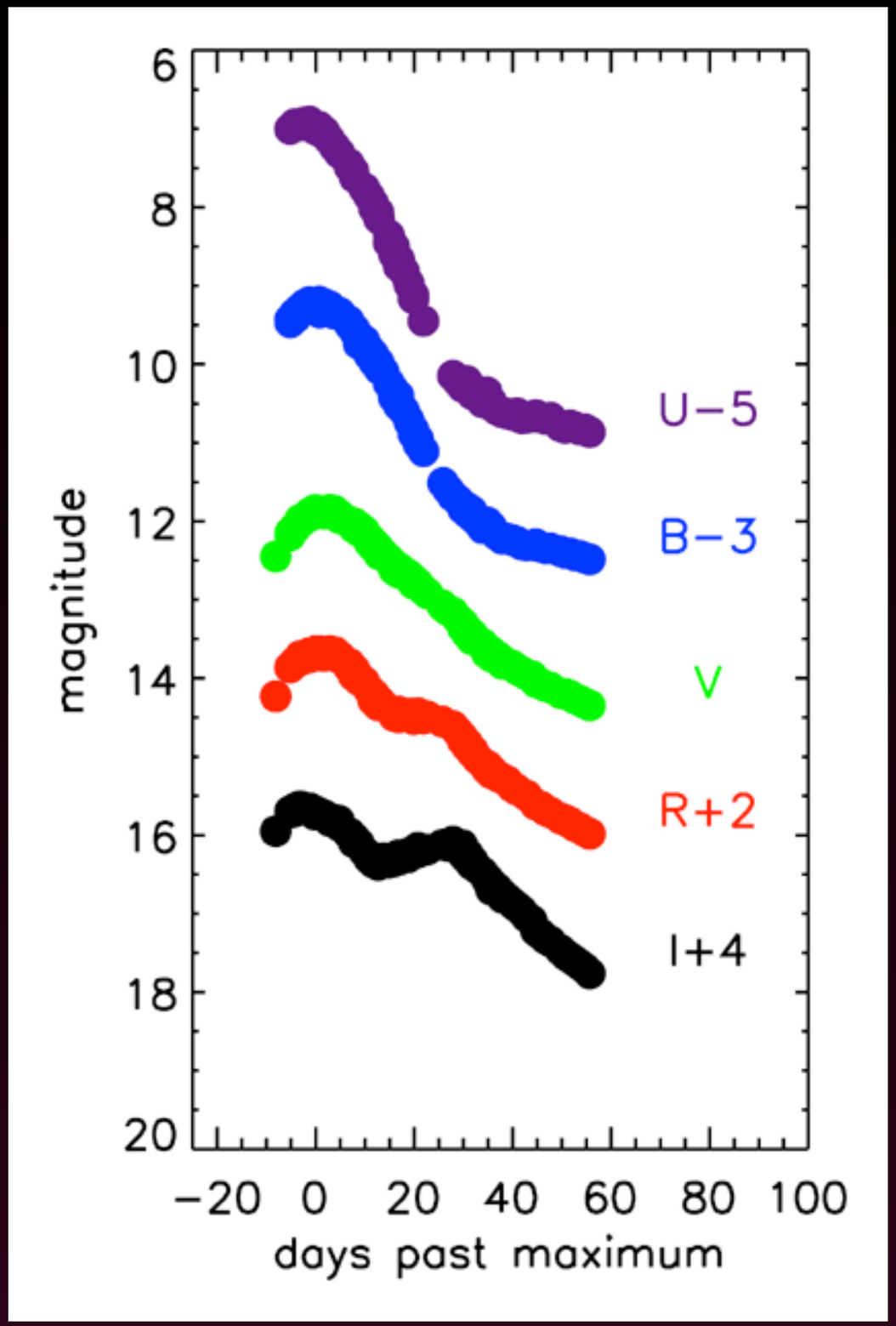


Thermonuclear (Type Ia) Supernovae

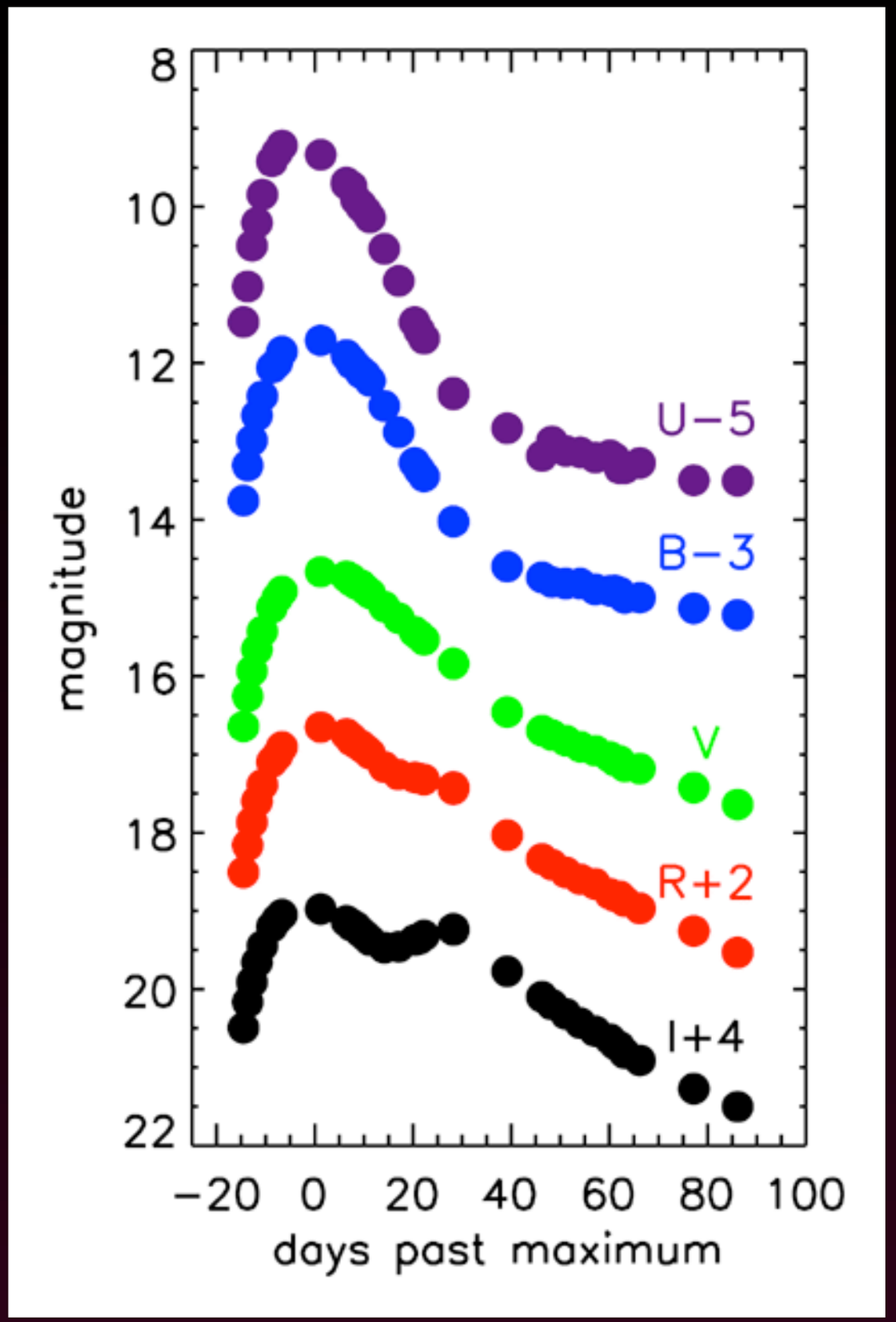


a complicated and uncertain story,
but we observe them to be very homogeneous

Some "Nearby" SN Ia Light Curves

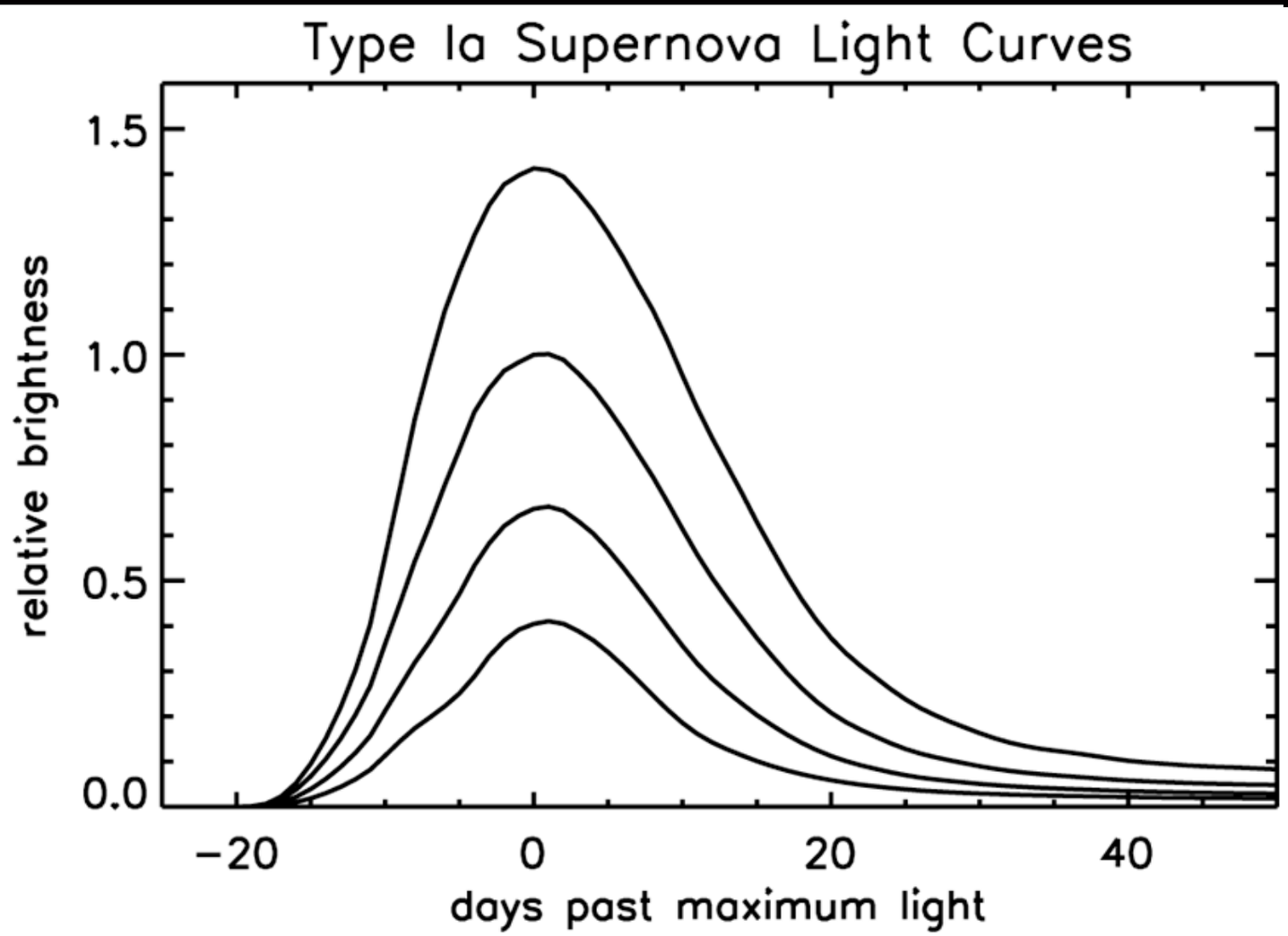


SN 1998bu in M 96



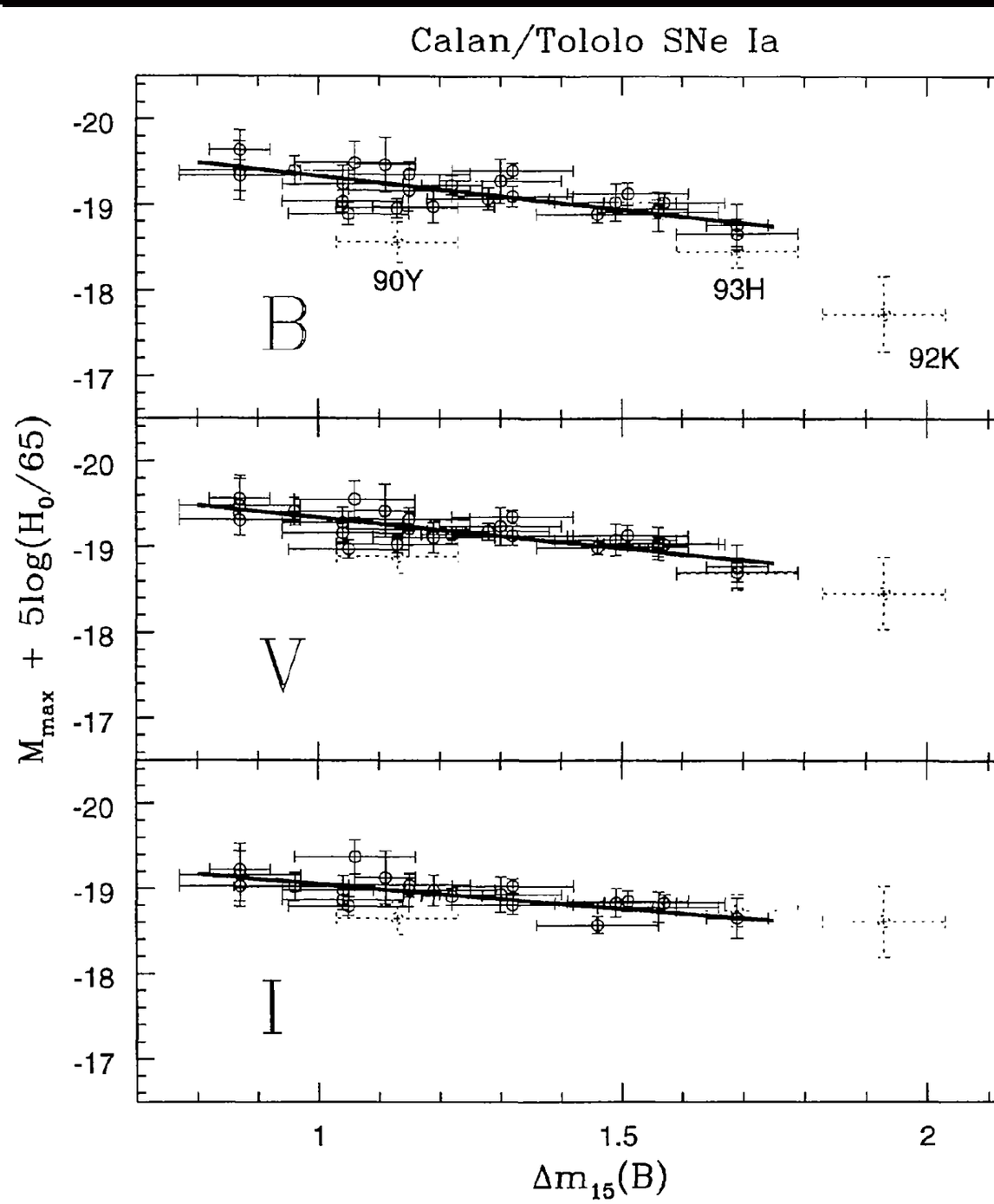
SN 2001V in NGC 3987

the groundbreaking work: Calán/Tololo SN Survey

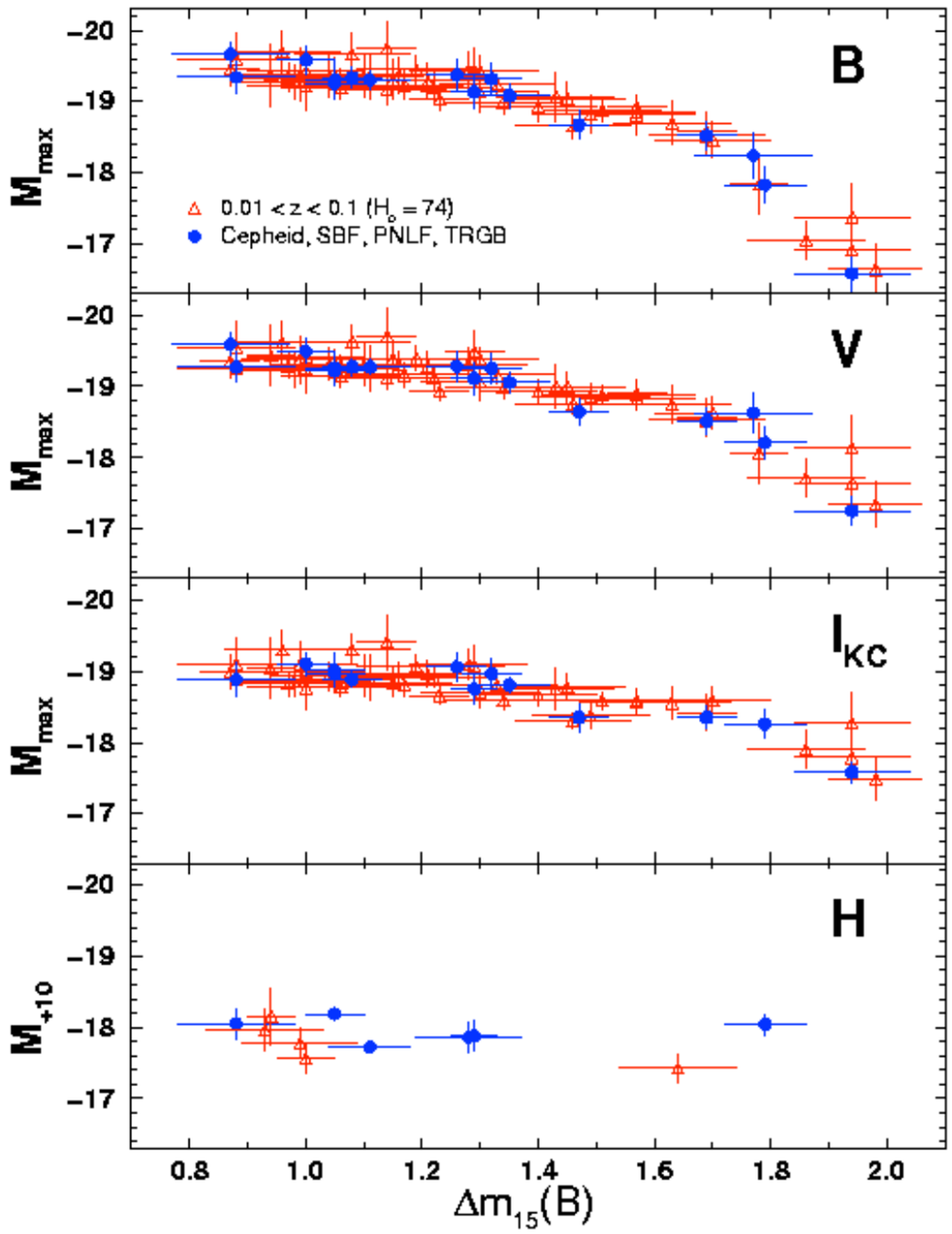


shape of the light curve lets us read the label on our cosmic light bulb

measuring colors lets us correct for attenuation of the light by dust



Phillips et al. (1993); Hamuy et al. (1996)



Krisciunas et al. (2006)

SN Ia are calibrated candles:

luminosity correlated with light-curve decline rate (Phillips relation)

multicolor templates constrain dust

Model the light curves:

$$\vec{m_V}(t-t_0) = \vec{M_V^0} + \mu_0 + \vec{\zeta_V} A_V^0 + \vec{P_V}\Delta + \vec{Q_V}\Delta^2$$
$$\vec{m_U}(t-t_0) = \vec{M_U^0} + \mu_0 + \vec{\zeta_U}\,(\alpha_U + \beta_U/R_V)\,A_V^0 + \vec{P_U}\Delta + \vec{Q_U}\Delta^2$$
$$\vec{m_B}(t-t_0) = \vec{M_B^0} + \mu_0 + \vec{\zeta_B}\,(\alpha_B + \beta_B/R_V)\,A_V^0 + \vec{P_B}\Delta + \vec{Q_B}\Delta^2$$
$$\vec{m_R}(t-t_0) = \vec{M_R^0} + \mu_0 + \vec{\zeta_R}\,(\alpha_R + \beta_R/R_V)\,A_V^0 + \vec{P_R}\Delta + \vec{Q_R}\Delta^2$$
$$\vec{m_I}(t-t_0) = \vec{M_I^0} + \mu_0 + \vec{\zeta_I}\,(\alpha_I + \beta_I/R_V)\,A_V^0 + \vec{P_I}\Delta + \vec{Q_I}\Delta^2$$

- observations: $\vec{m_X}(t)$
- fixed, calculate from spectra: $\vec{\zeta_X}\ \alpha_X\ \beta_X$
- template vectors: $\vec{M_X^0}\ \vec{P_X}\ \vec{Q_X}$
- model parameters: $t_0\ R_V\ A_V^0\ \Delta\ \mu_0$

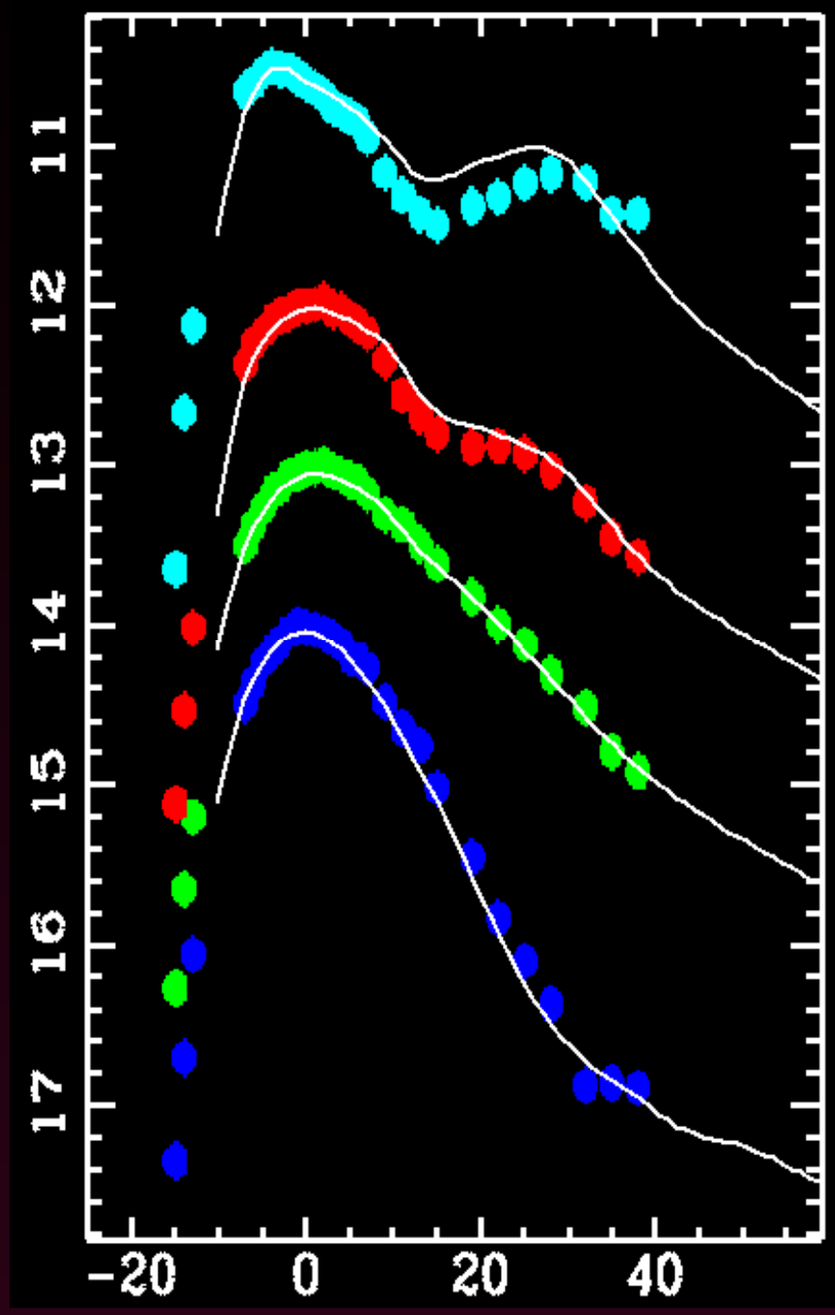
Fit the light curves, incorporate priors:

$$\chi^2 = \vec{r}^{\,T} C^{-1} \vec{r} - 2\ln \hat{p}(t_0, \mu_0, \Delta, A_V^0, R_V)$$

MLCS2k2
Jha, Riess, & Kirshner (2007)

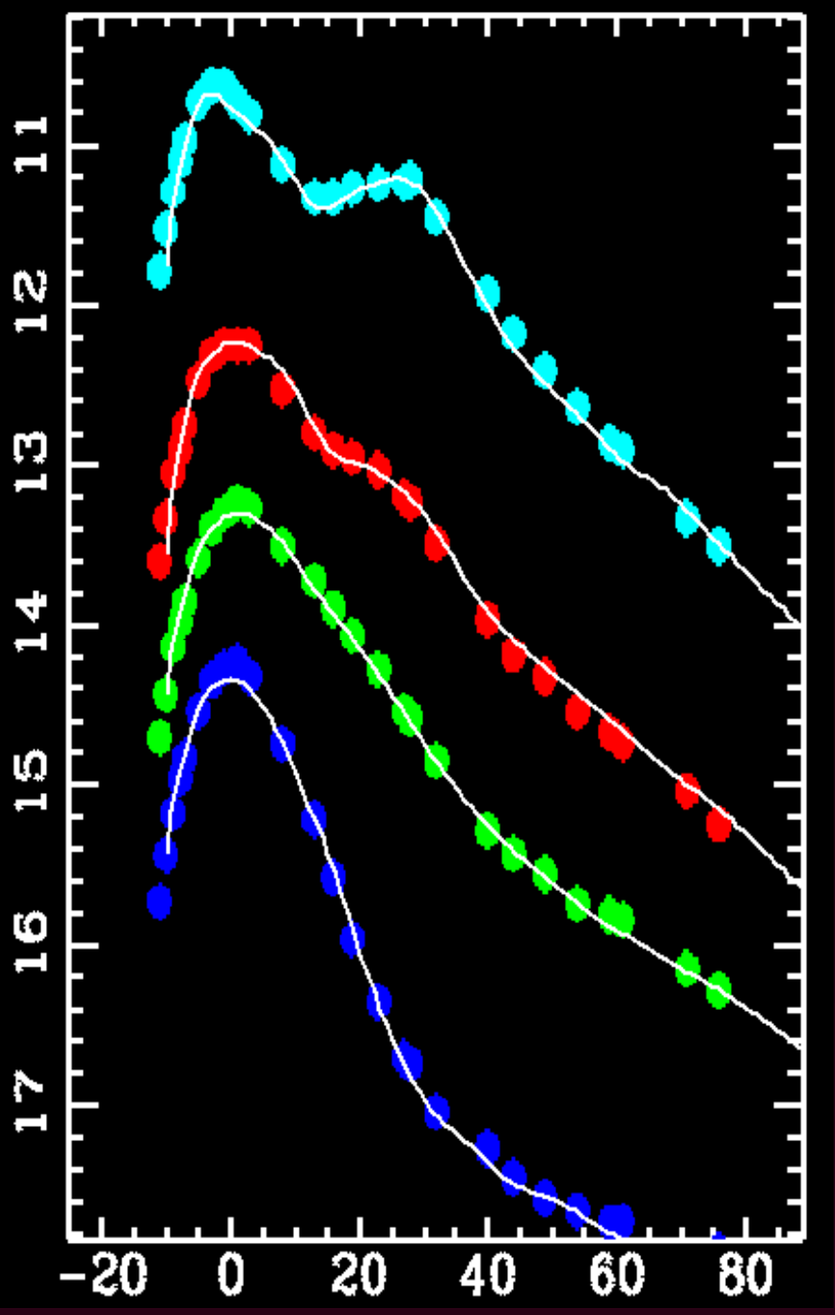
MLCS2k2 light curve fits

KAIT BVRI photometry



μ = 33.46 ± 0.07 mag

Ganeshalingam et al. (2009, in prep)



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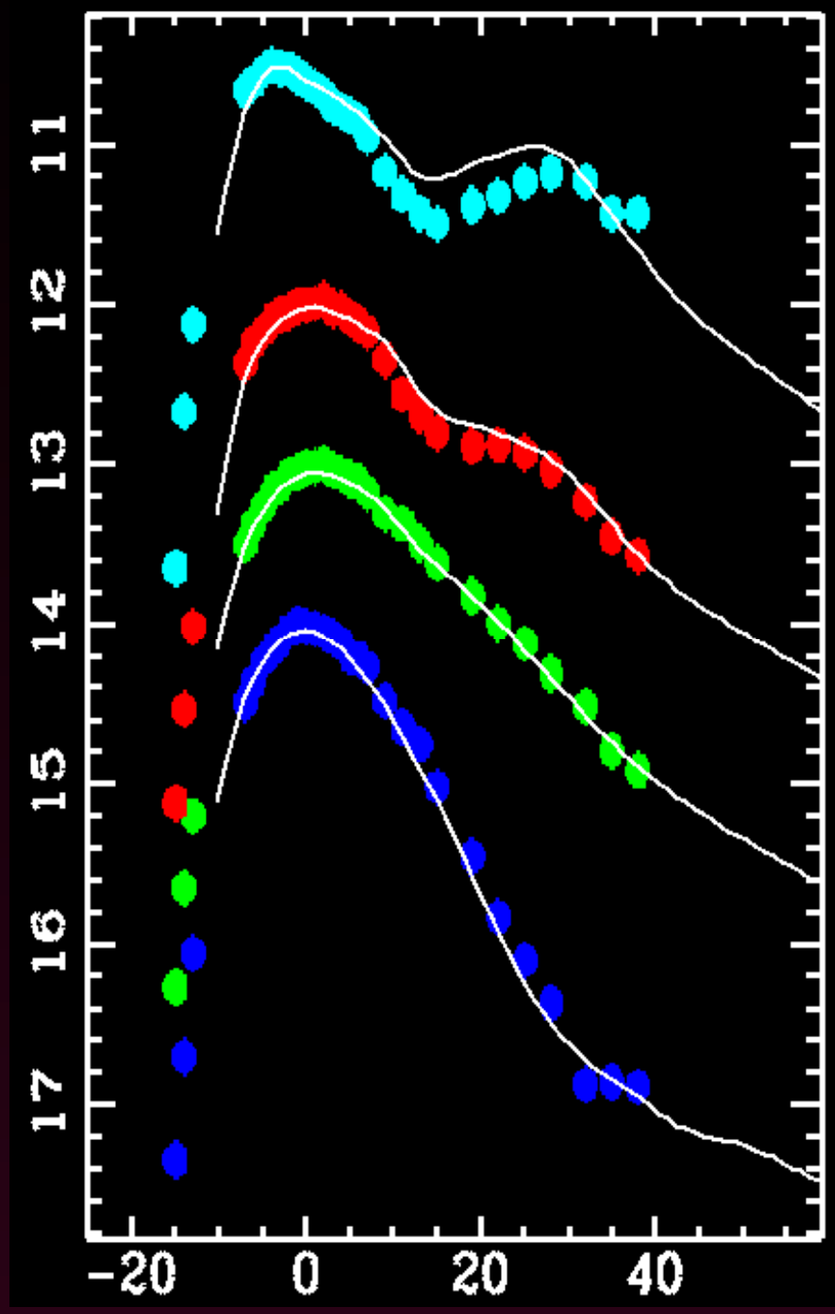

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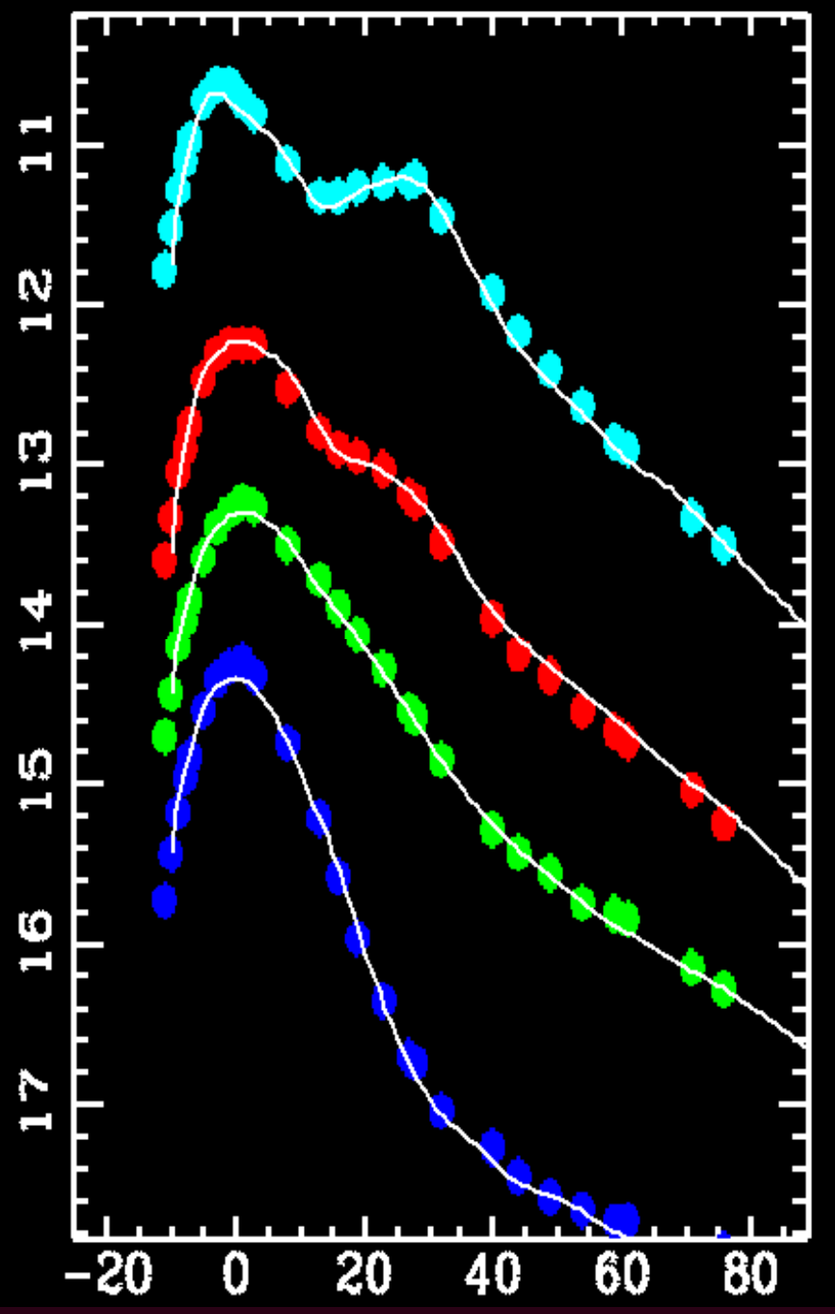

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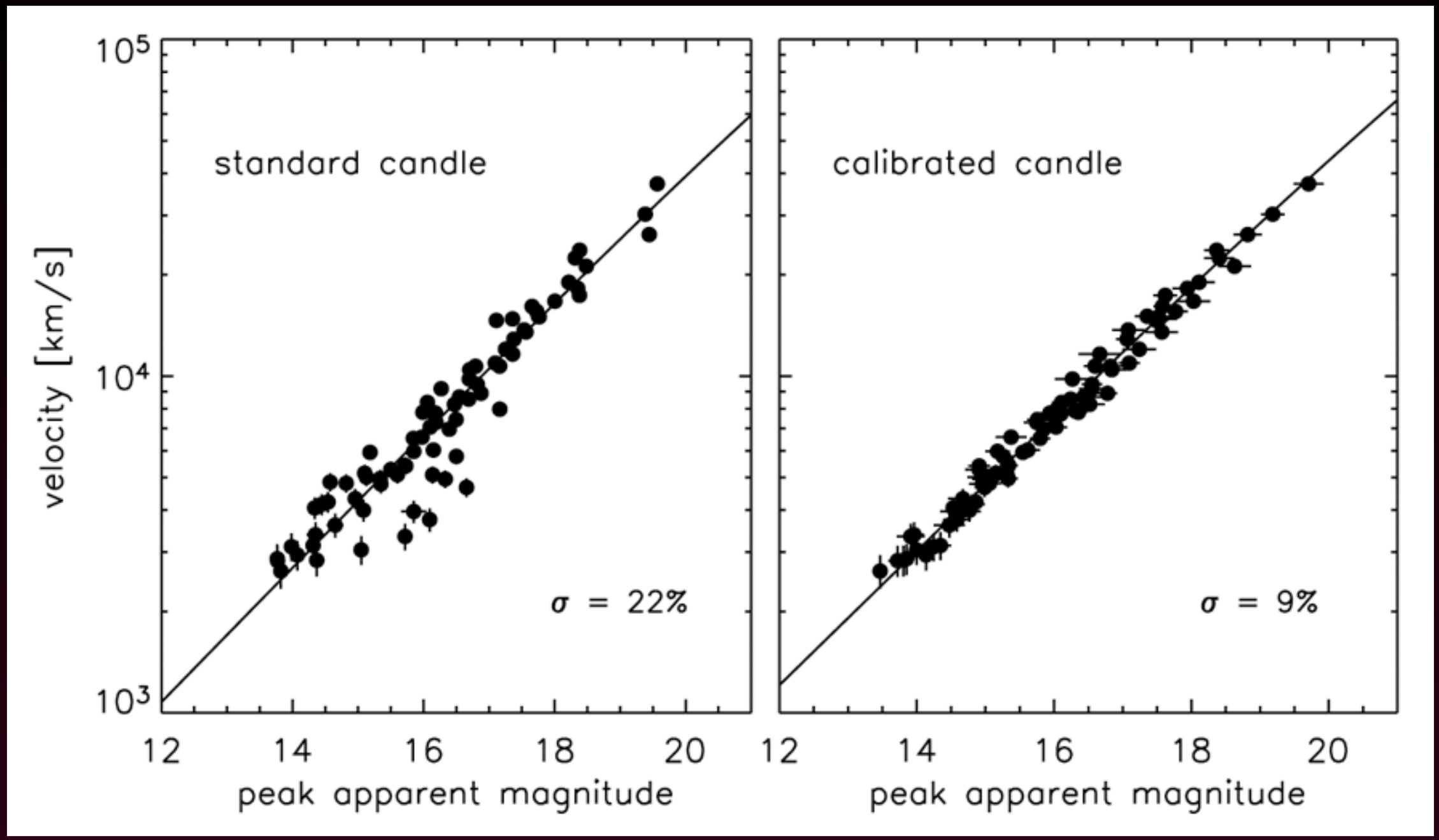
SN 1999cp and SN 2002cr, both in NGC 5468

Correcting for Intrinsic Variations and Dust



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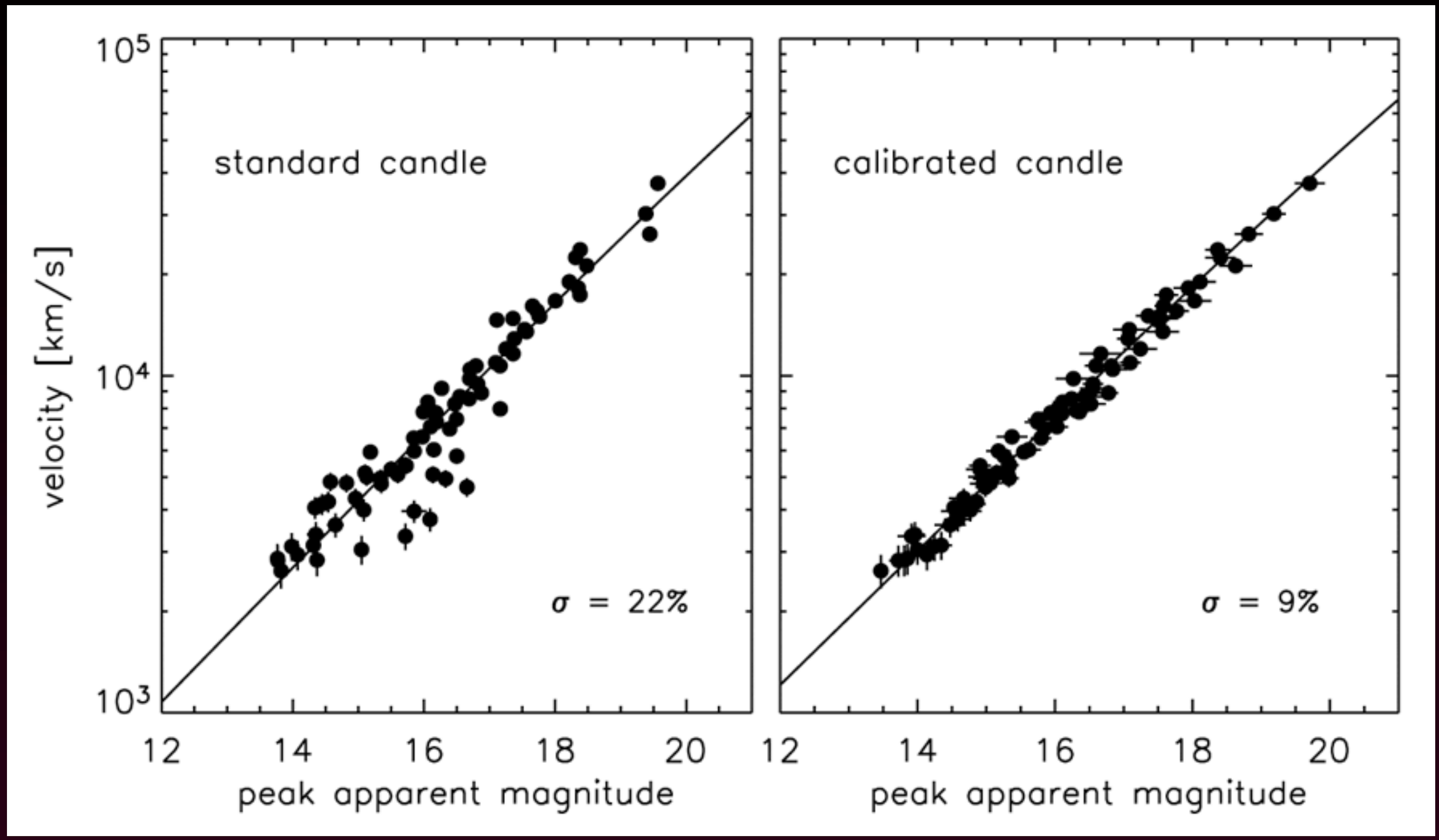
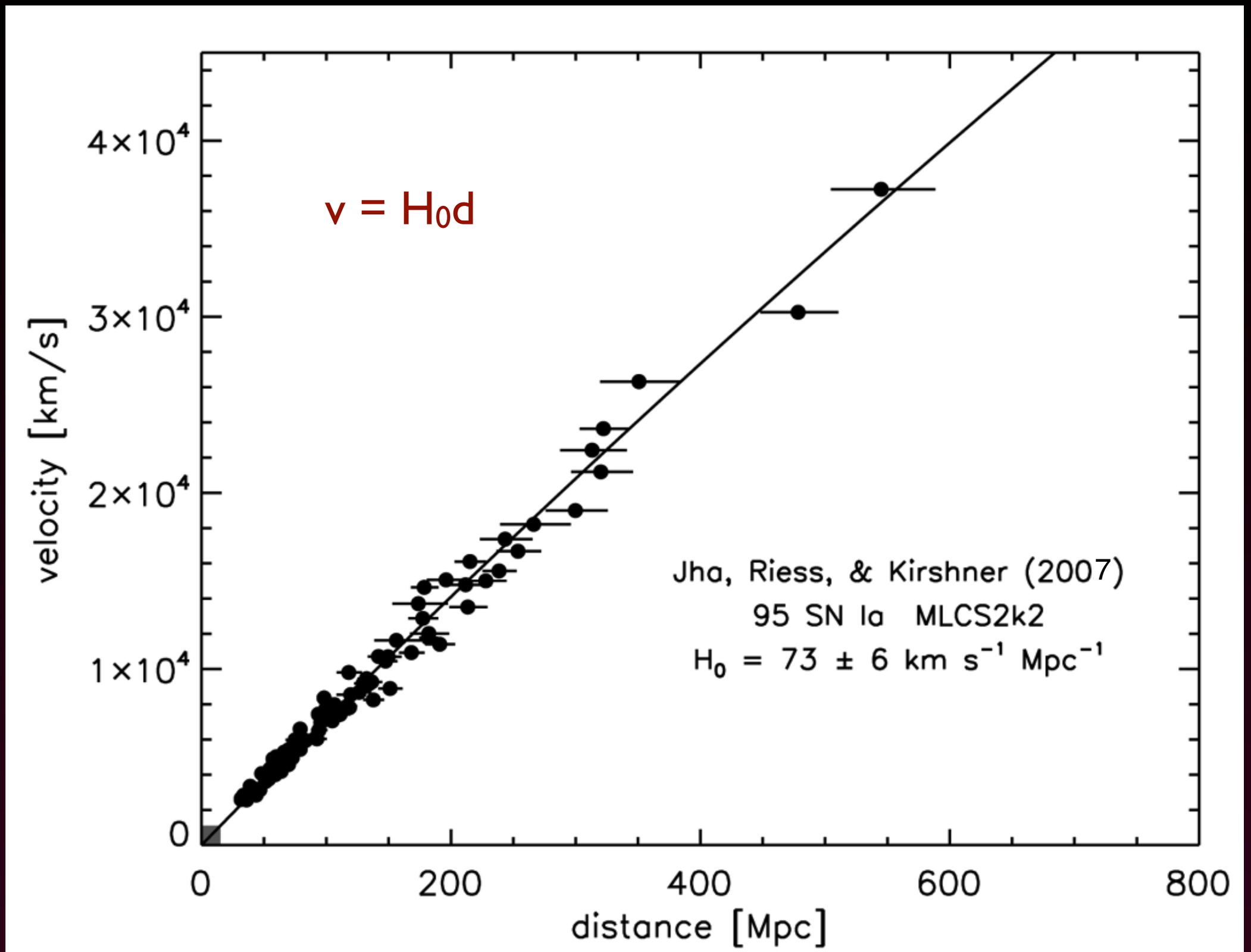
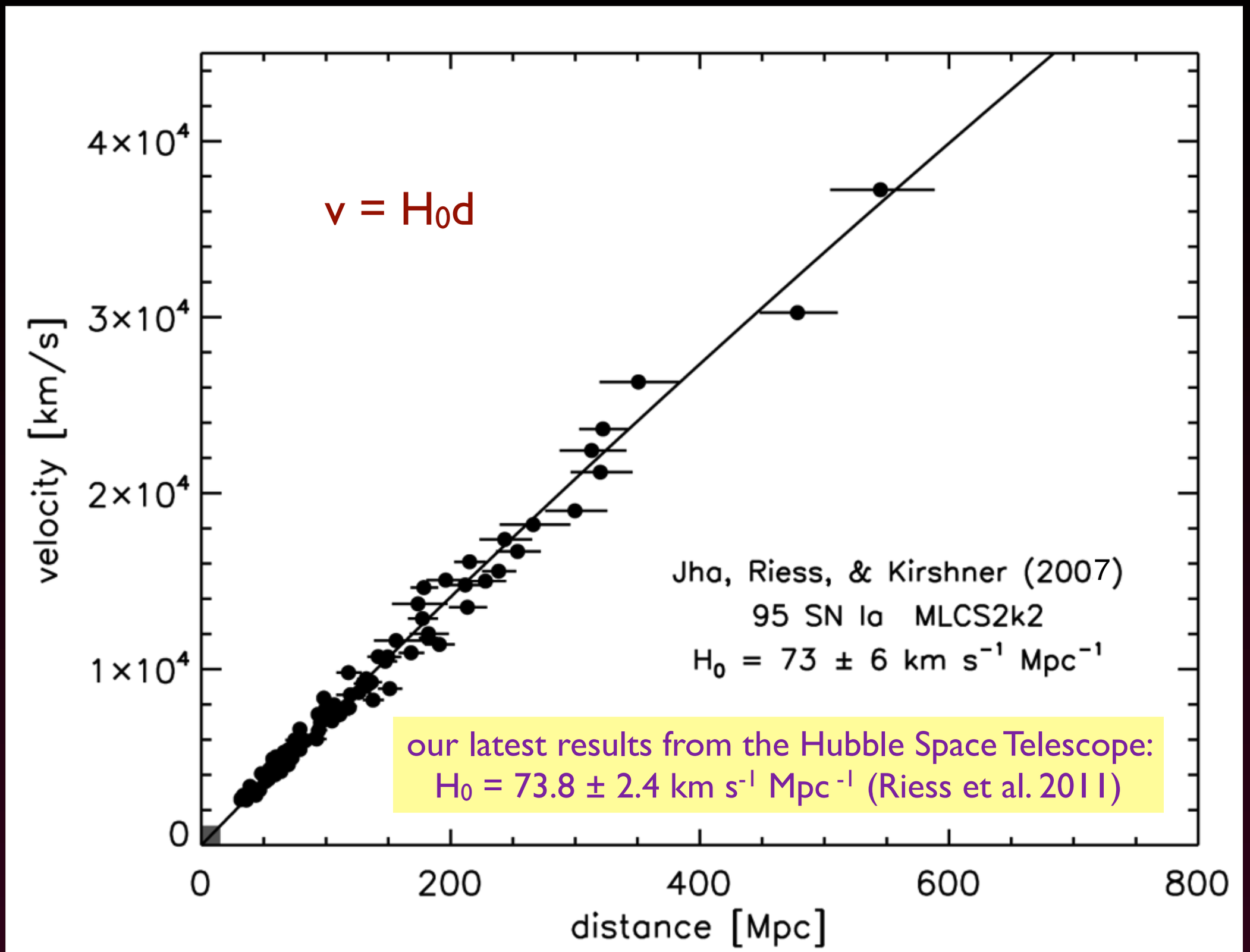


empirical validation that the method works!

Hubble's Law extended



Hubble's Law extended



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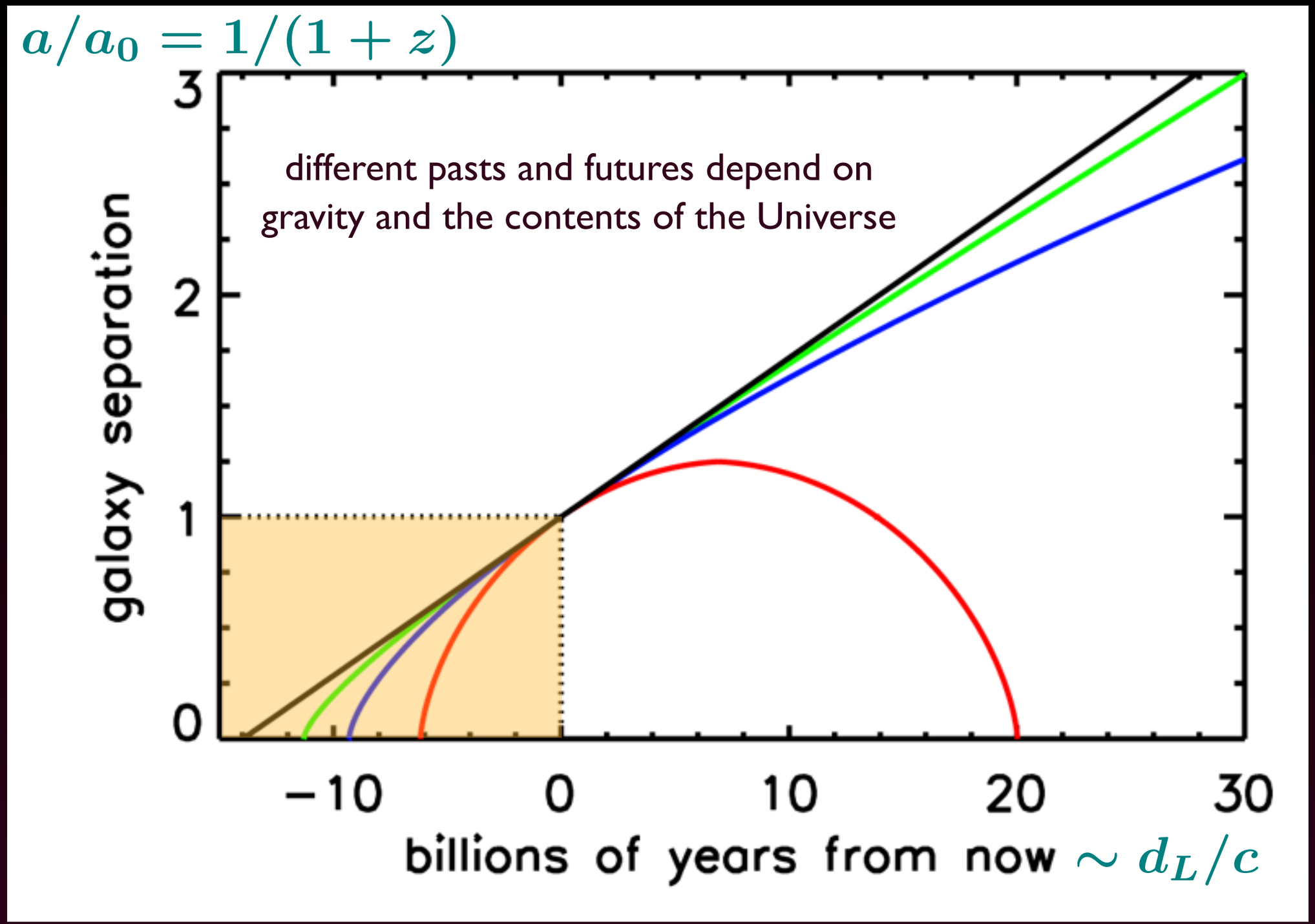

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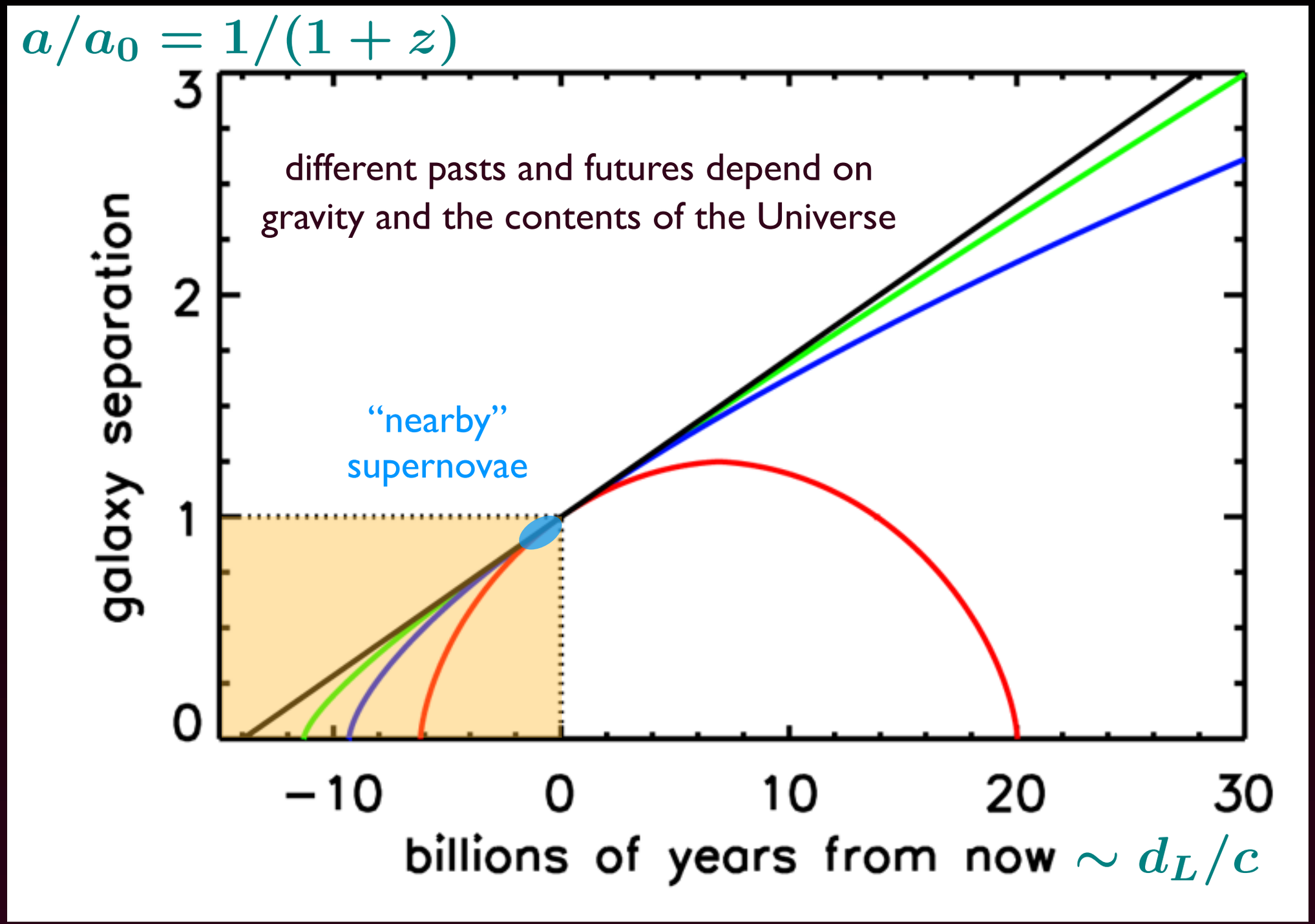


to see these curves diverge, we need to look farther back in time:
distant (high-redshift) type Ia supernovae

Finding Distant Supernovae

CTIO 4m

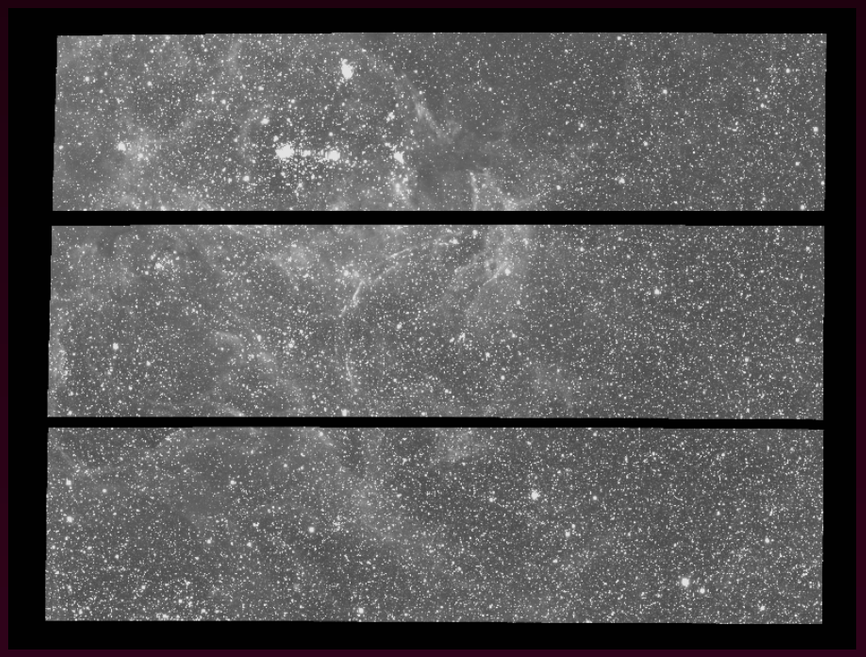
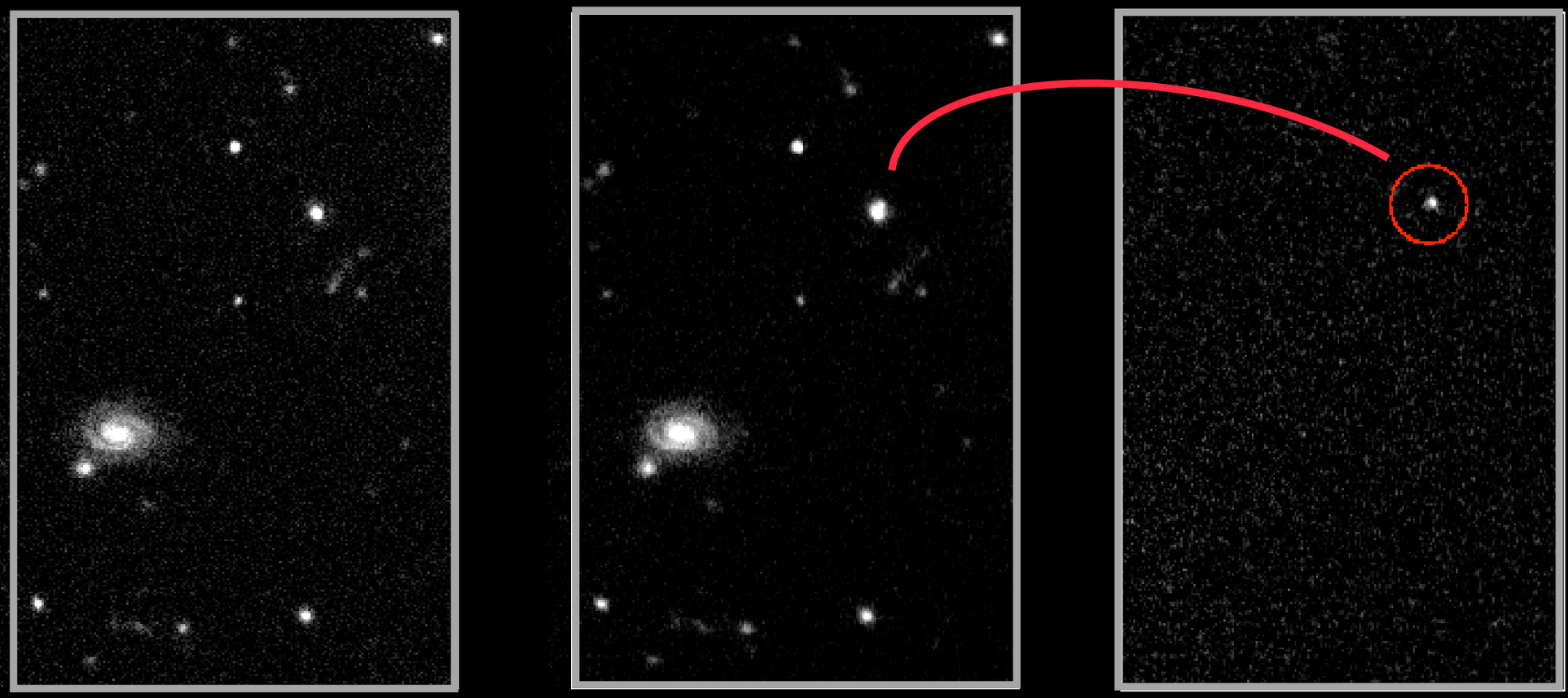


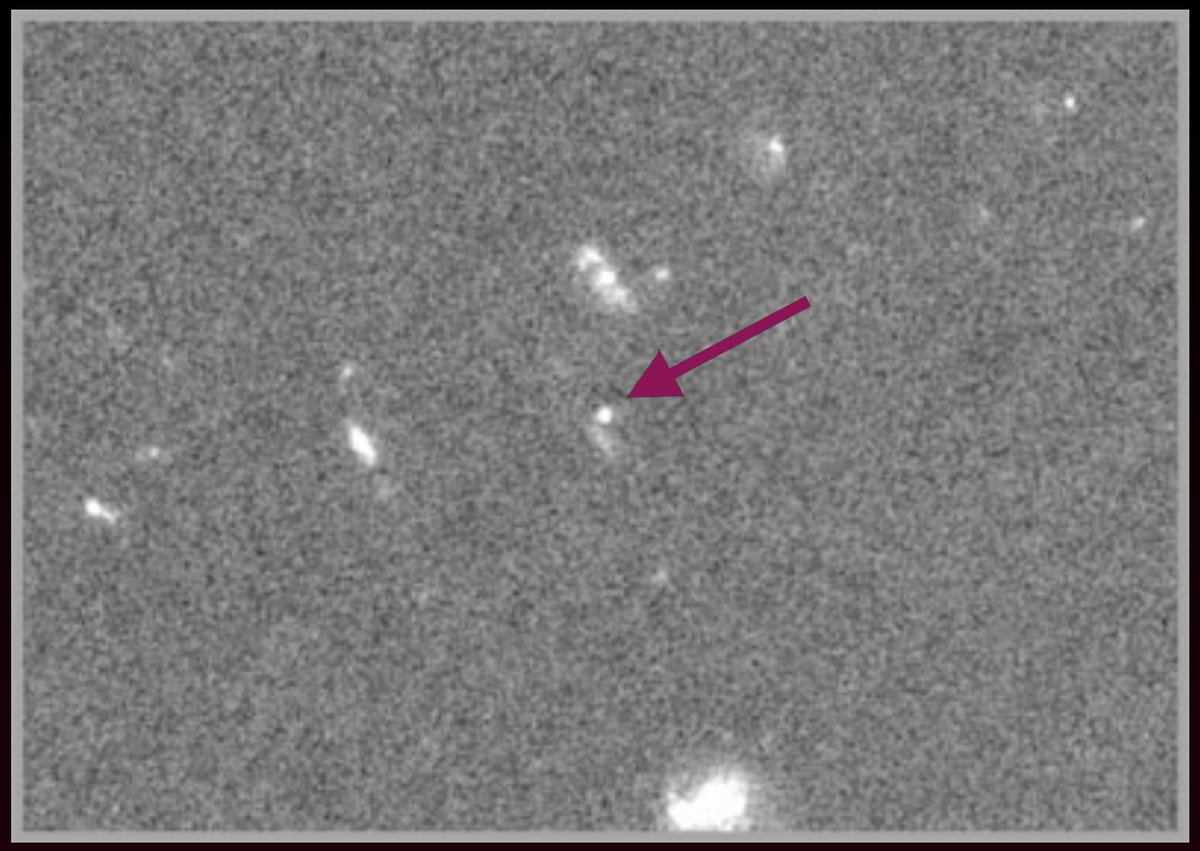
Image Subtraction

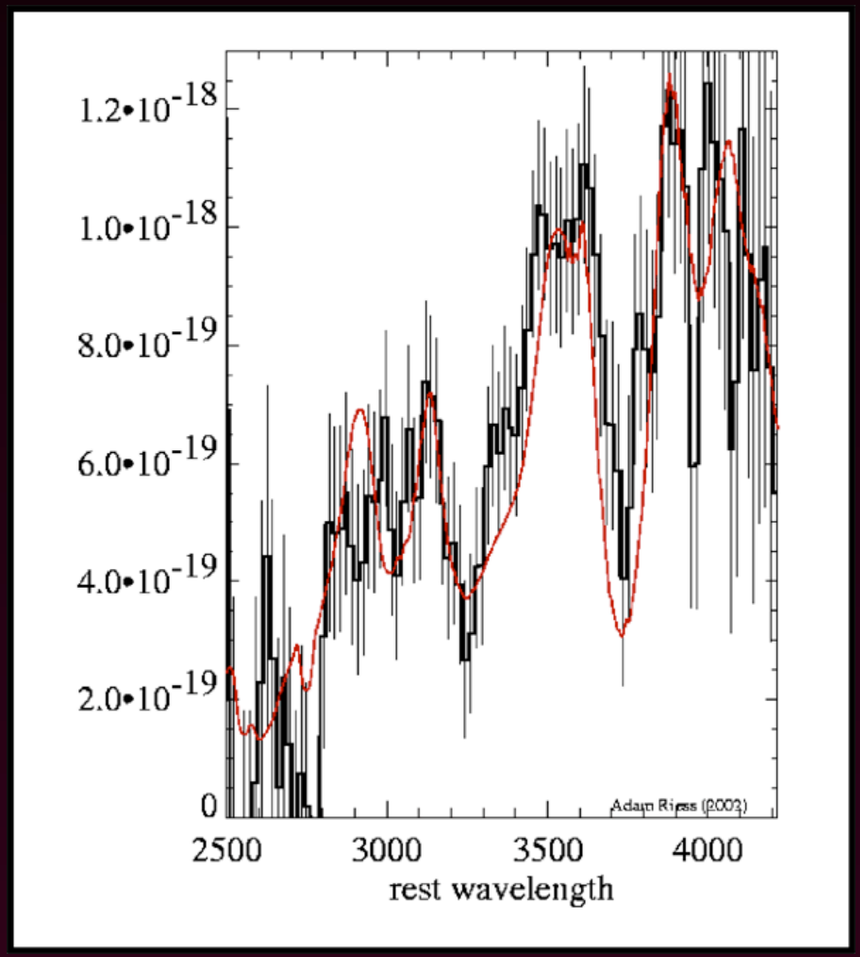
Epoch 1 | Epoch 2 (3 weeks later) | Epoch 2 - Epoch 1



(High-z Supernova Team)

A Distant Type Ia Supernova, z = 1.3

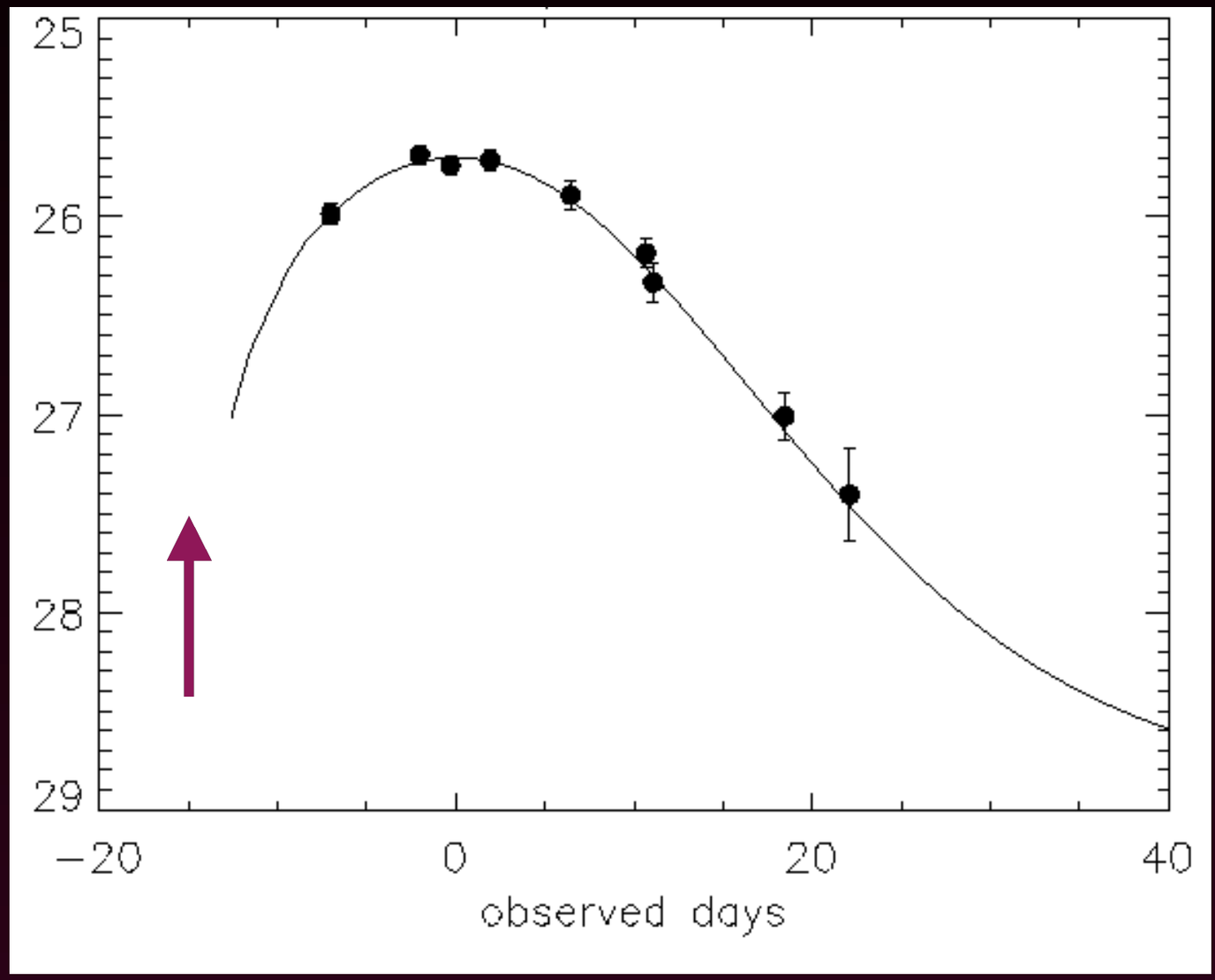




The Mighty Aphrodite

ACS z-band 1 orbit

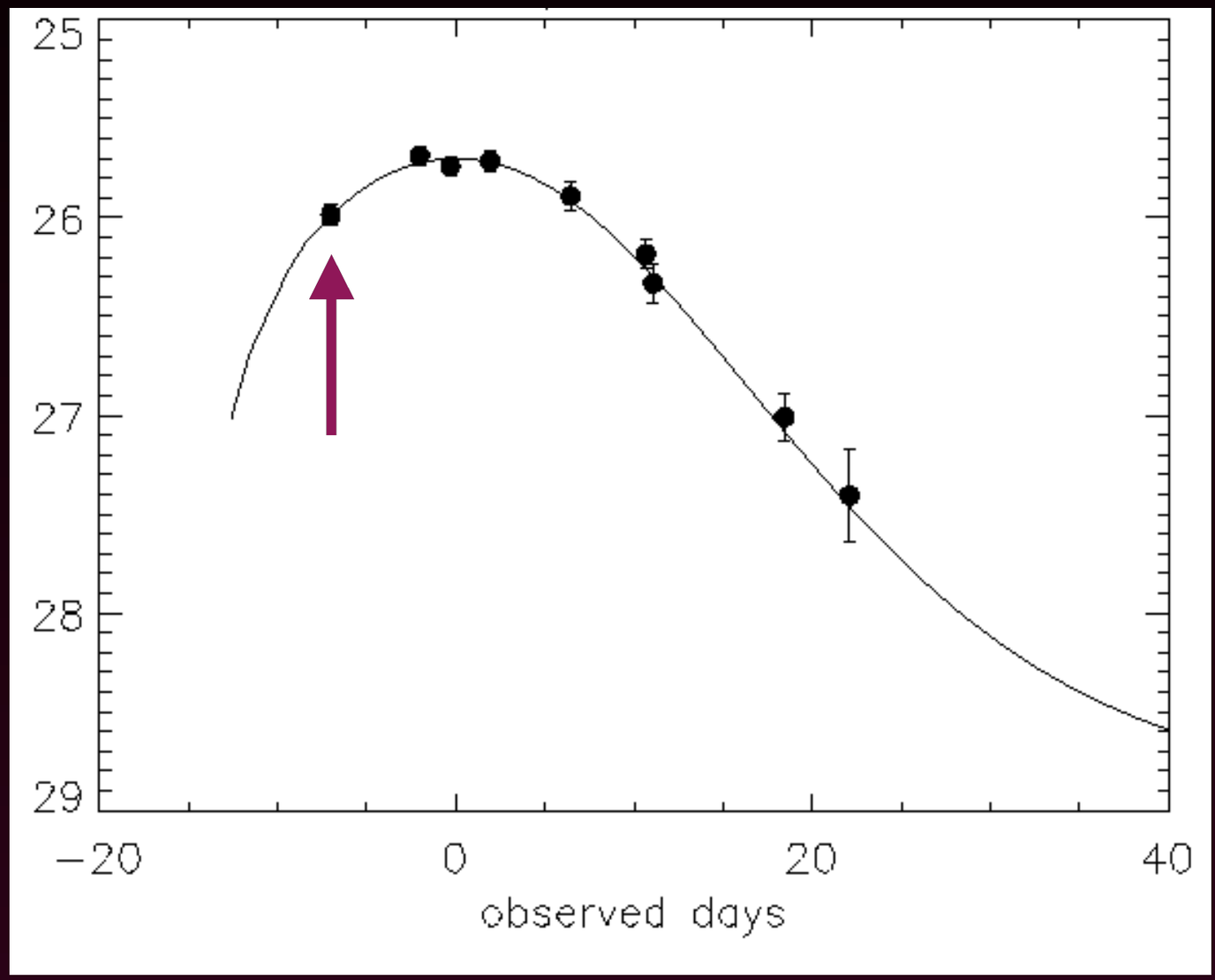
2002 August 01



The Mighty Aphrodite

ACS z-band 1 orbit

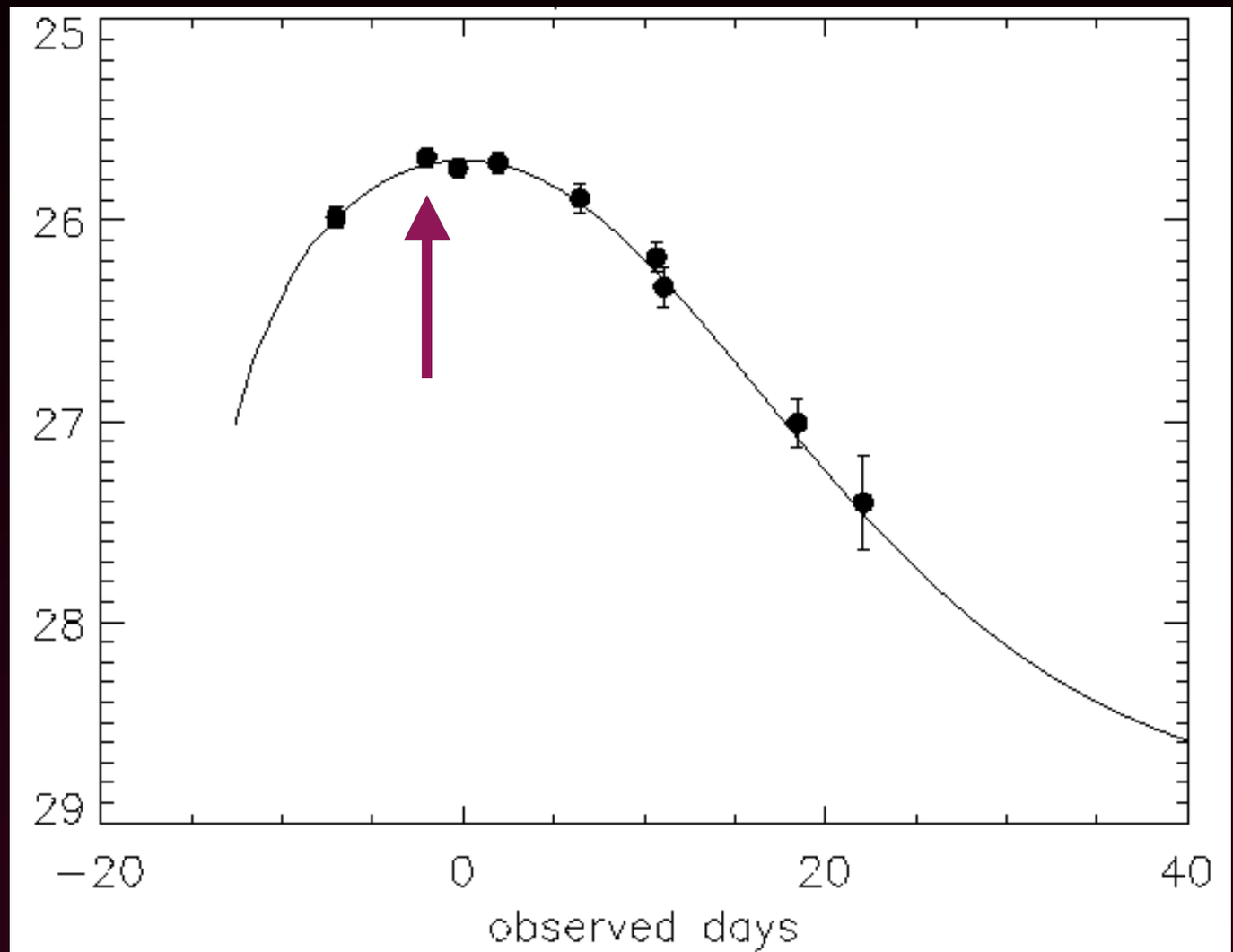
2002 September 22



The Mighty Aphrodite

ACS z-band 1 orbit

2002 October 01



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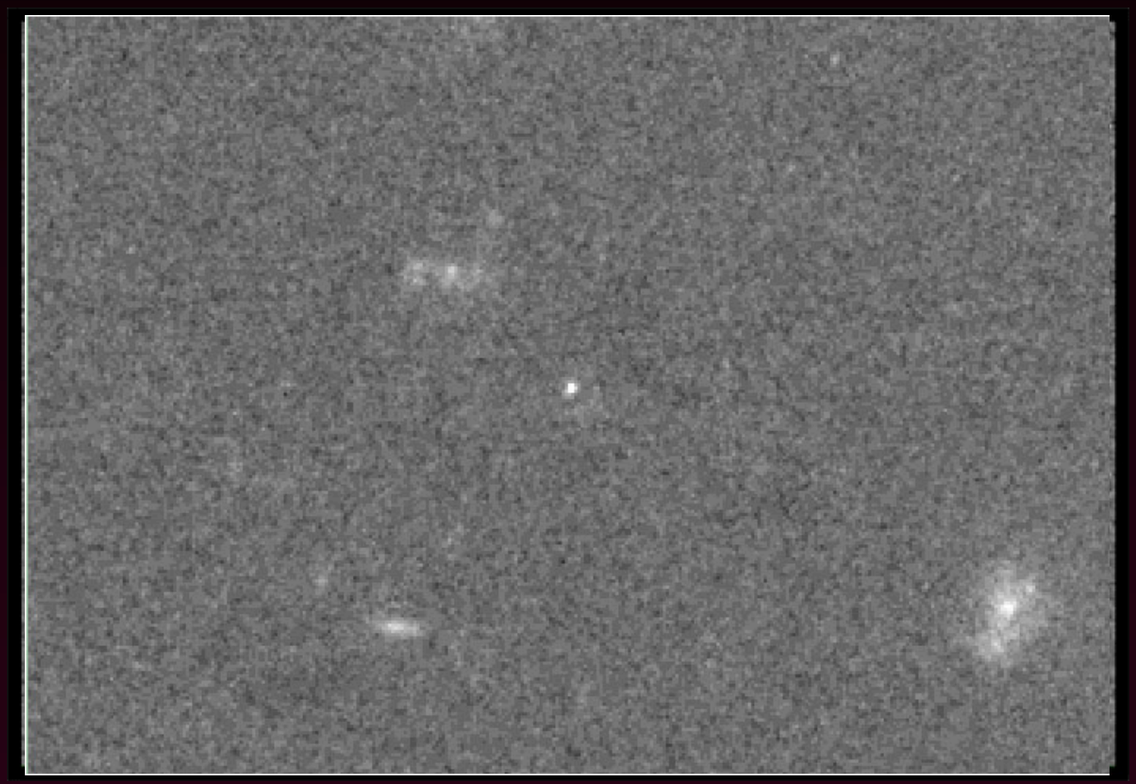
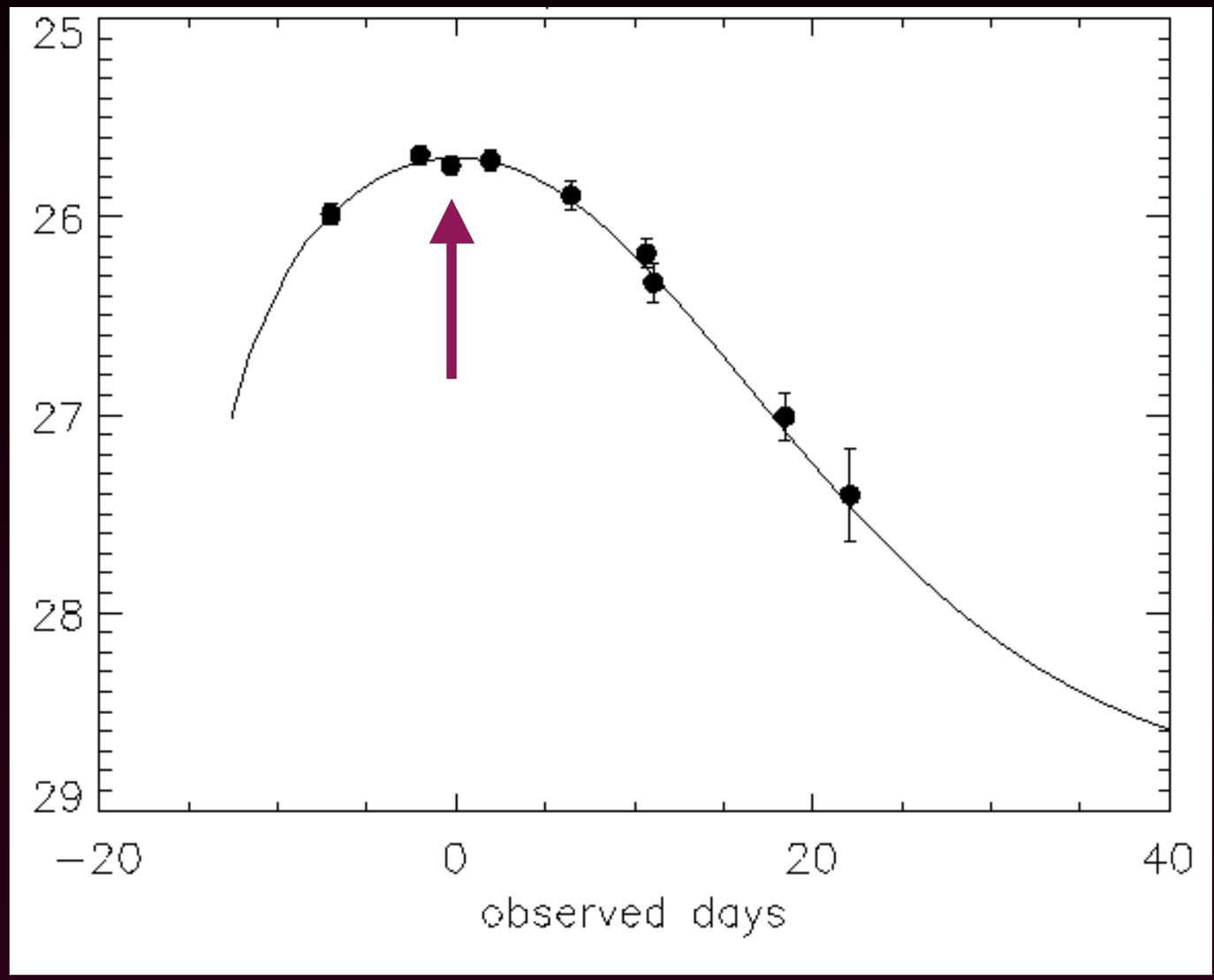


2002 October 05



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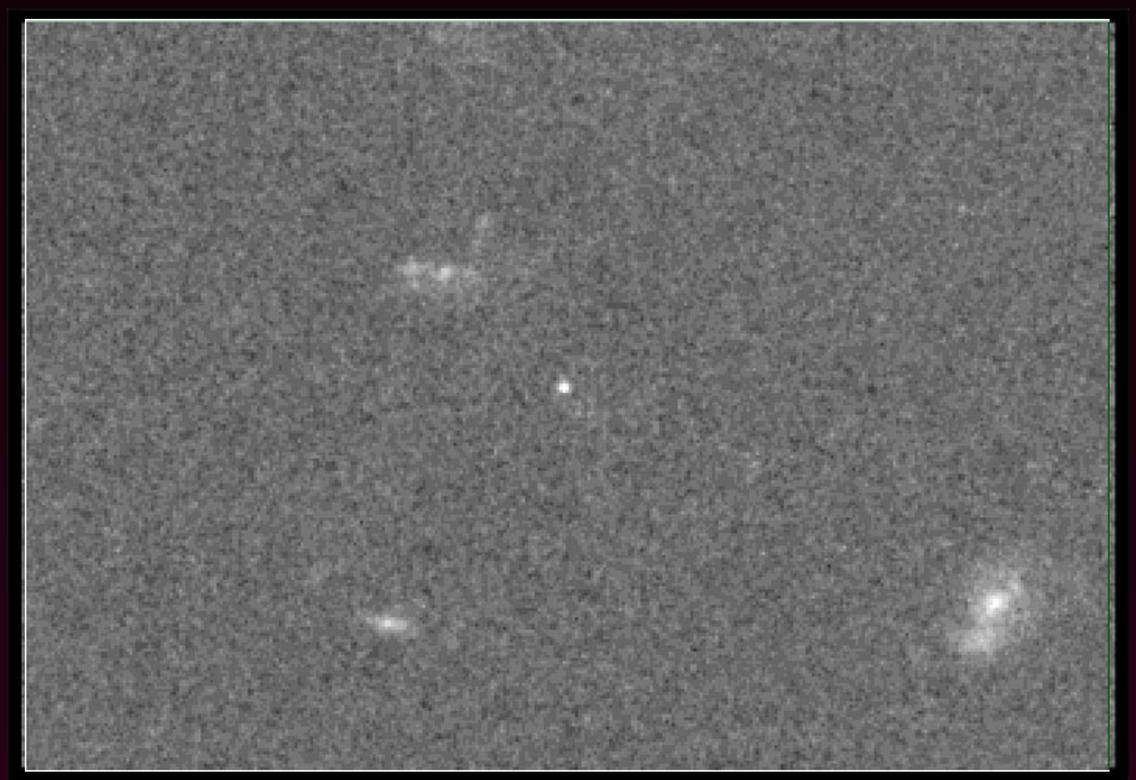
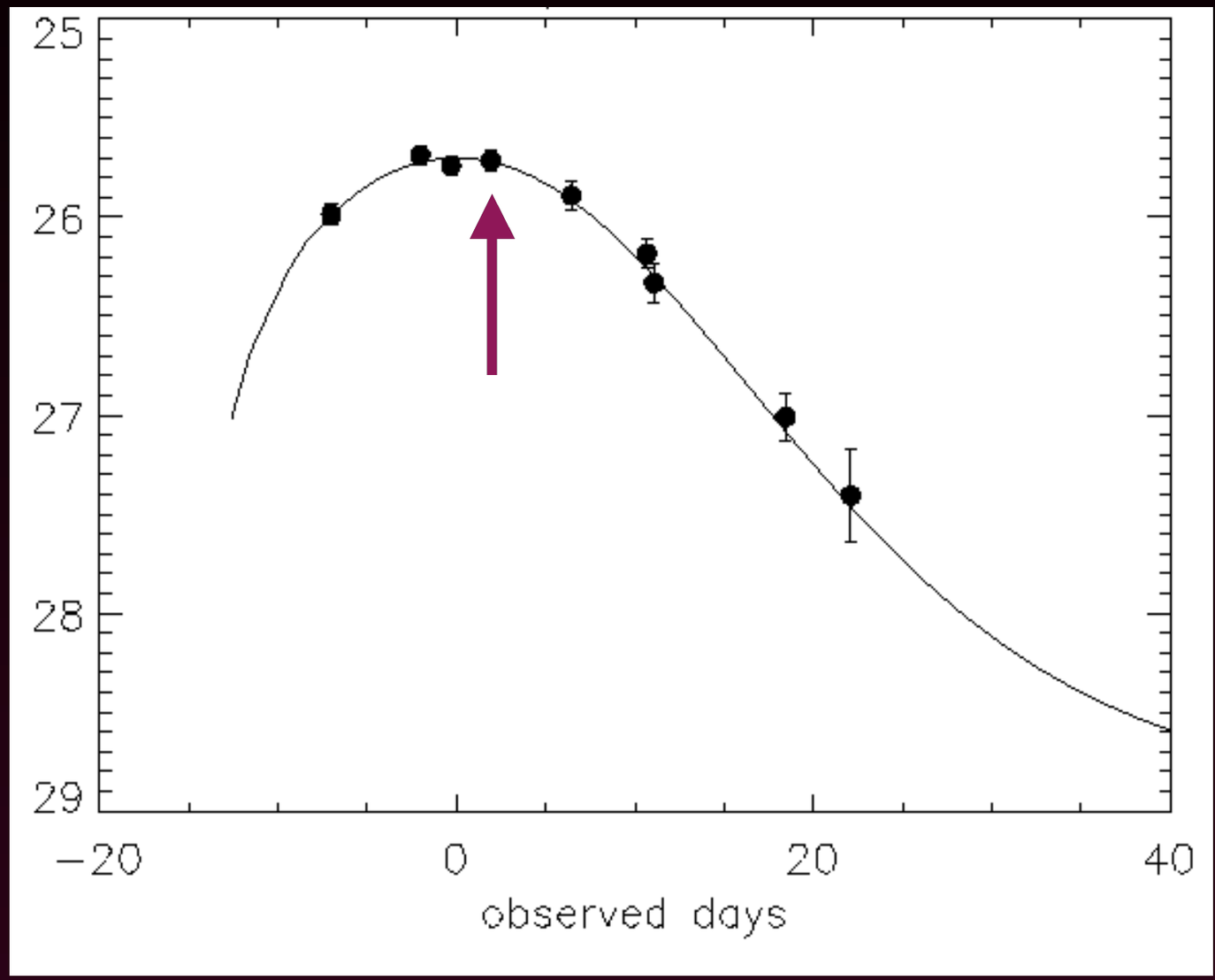


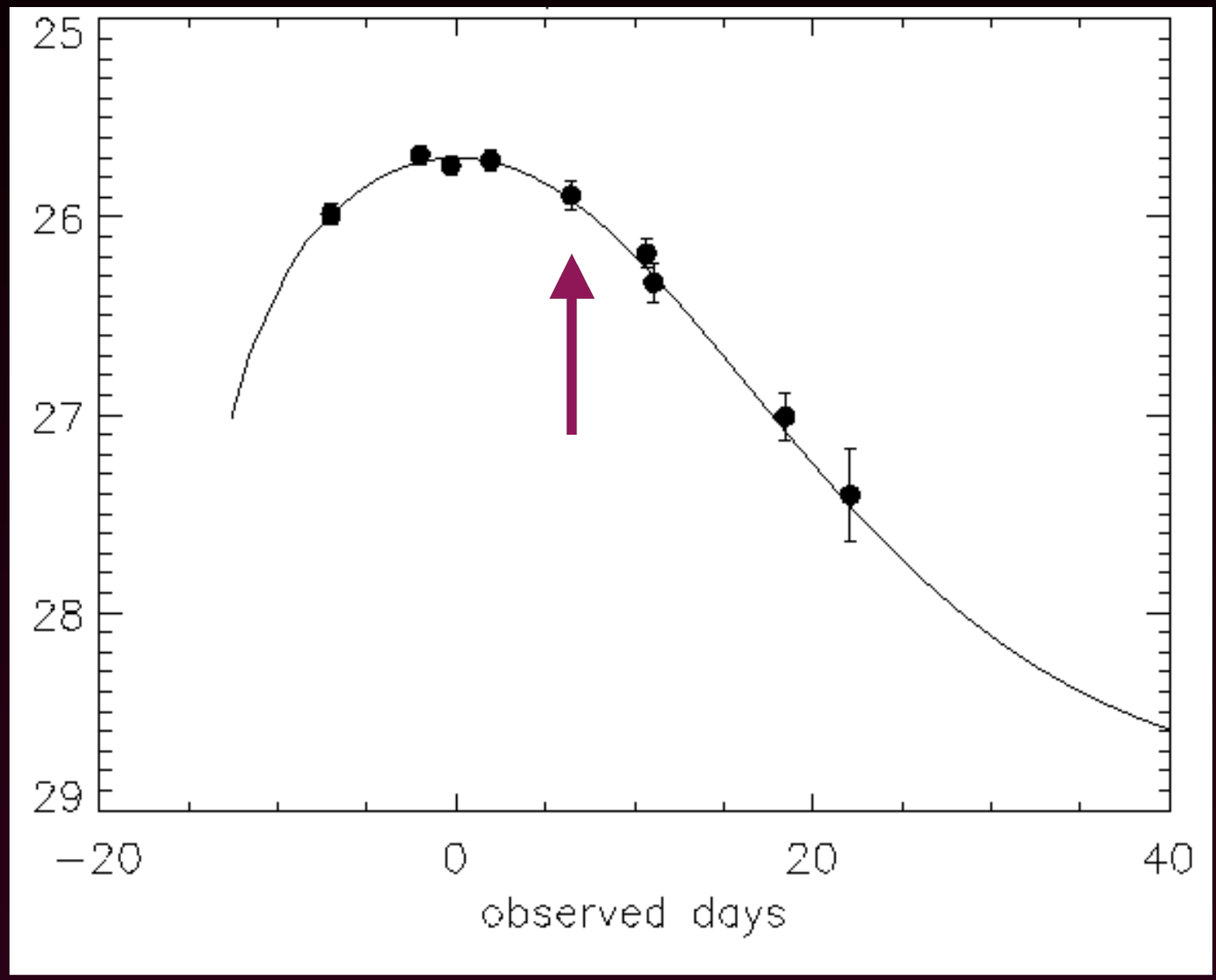
2002 October 10



The Mighty Aphrodite

ACS z-band 1 orbit

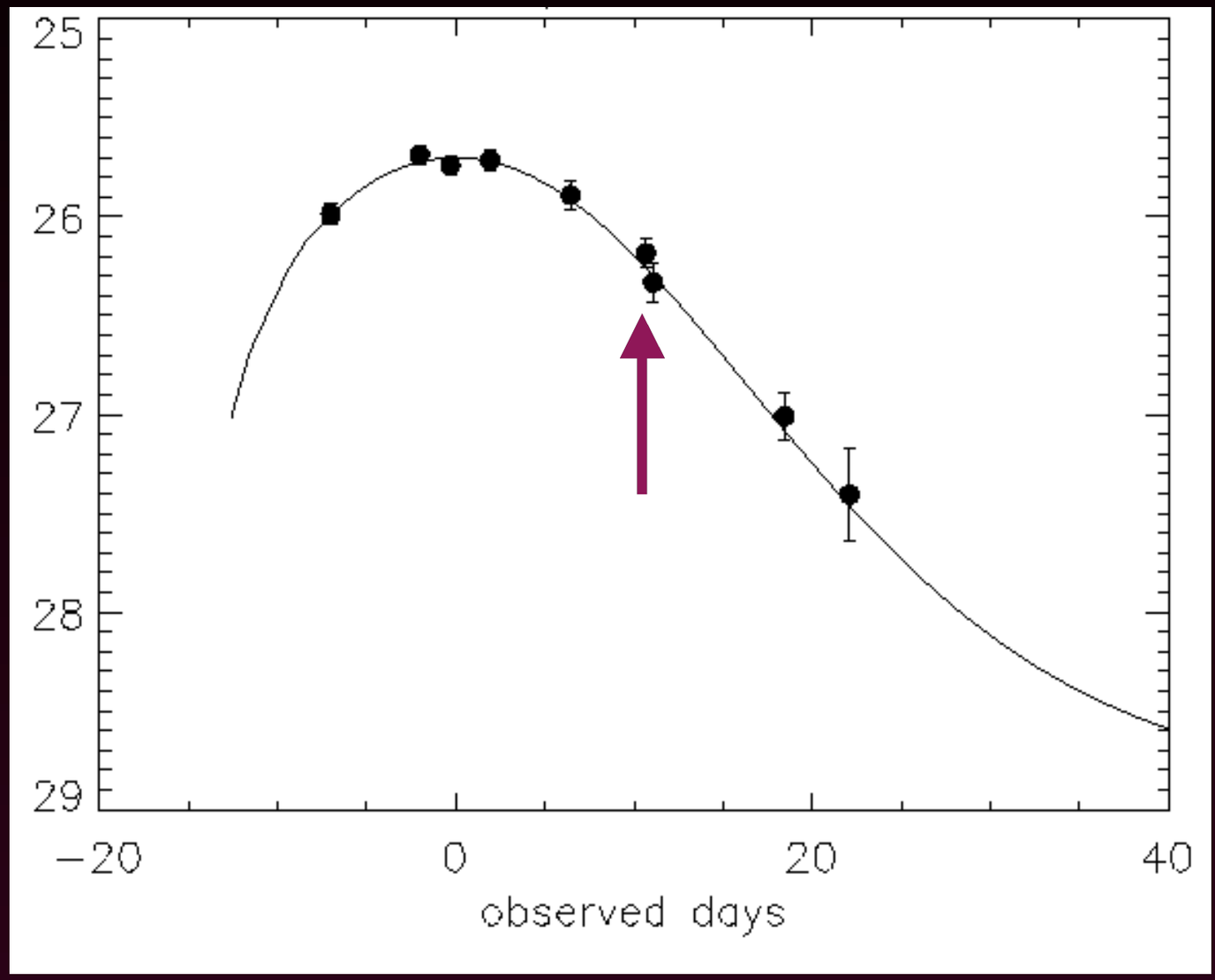
2002 October 20



The Mighty Aphrodite

ACS z-band 1 orbit

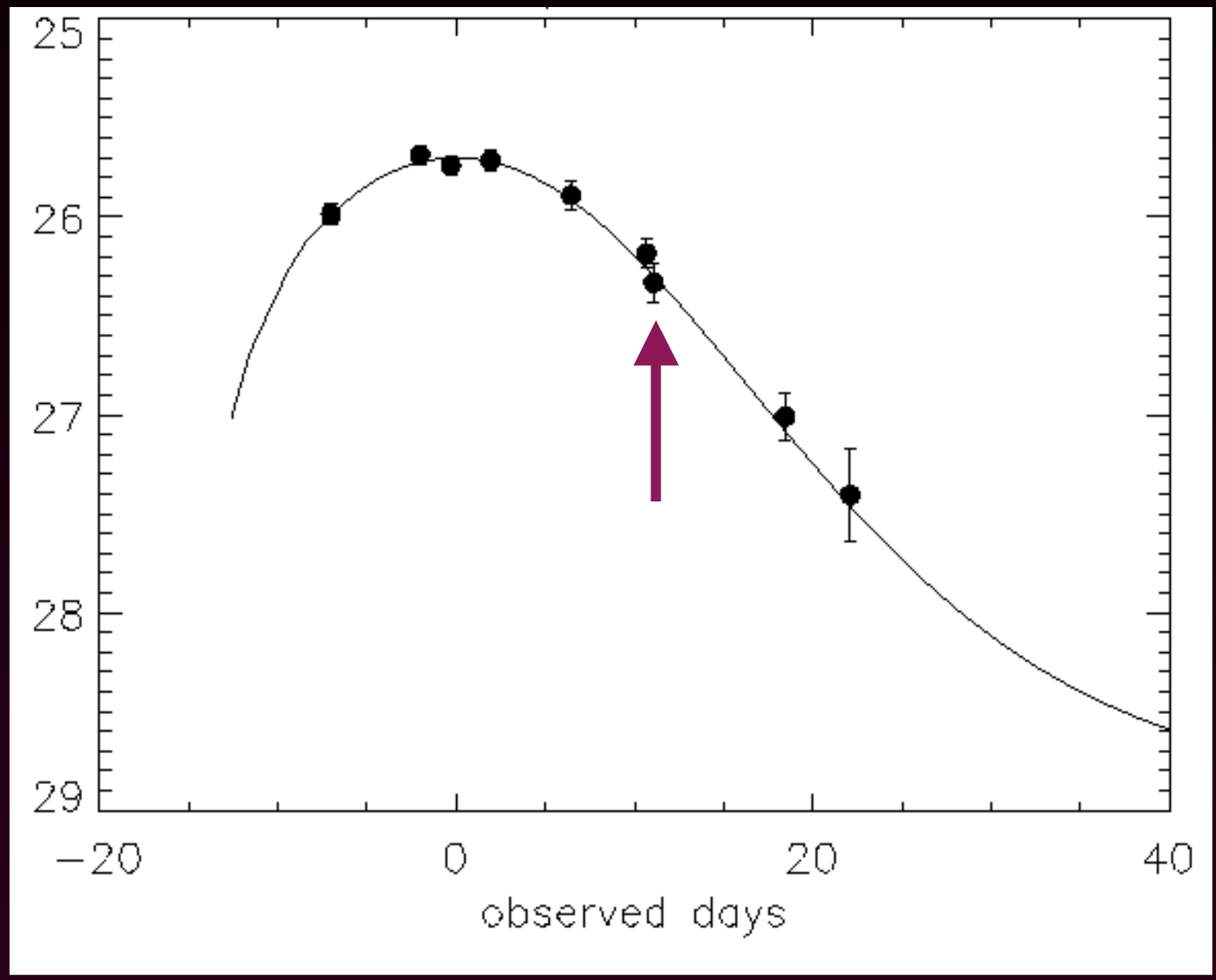
2002 October 30



The Mighty Aphrodite

ACS z-band 1 orbit

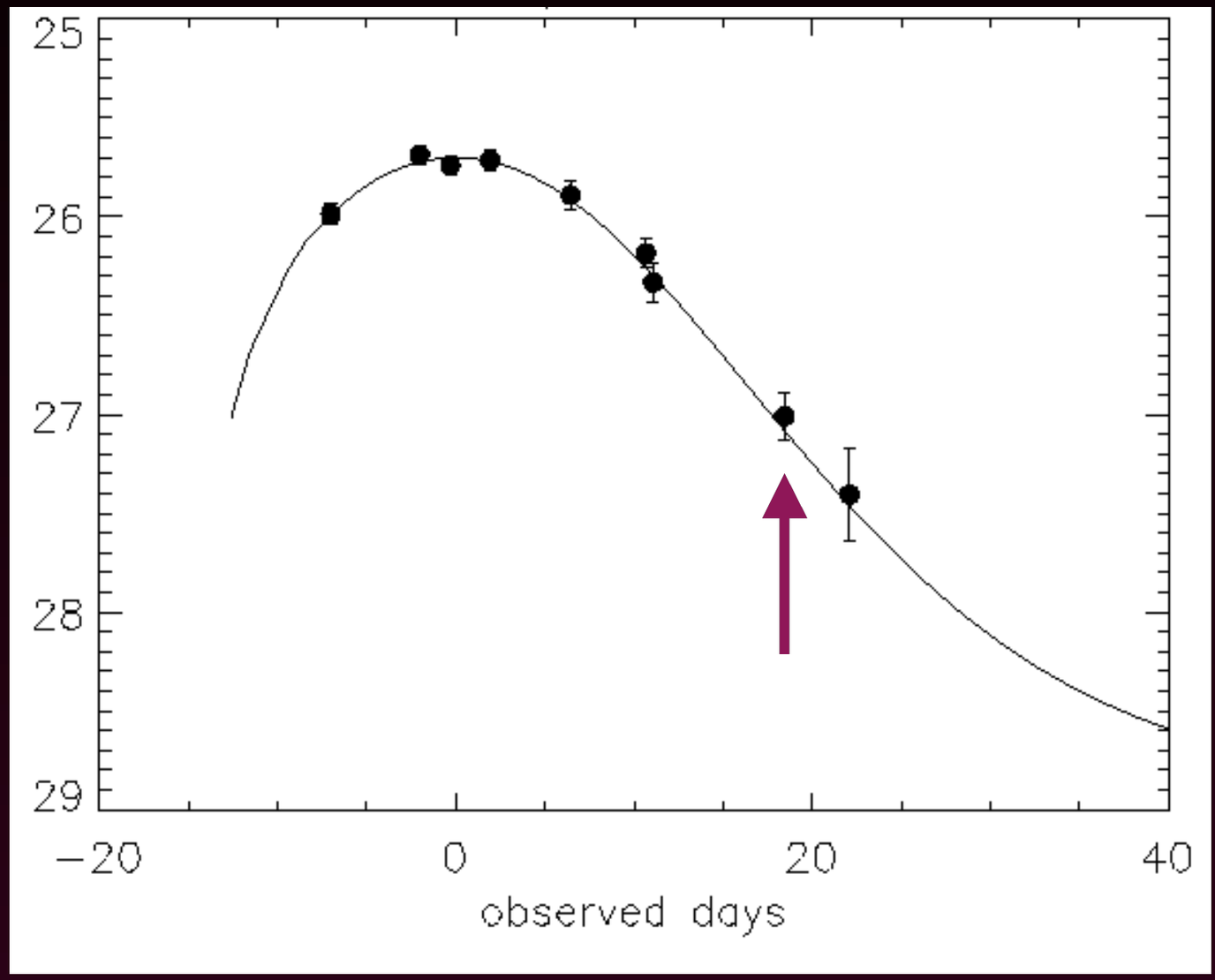
2002 October 31



The Mighty Aphrodite

ACS z-band 1 orbit

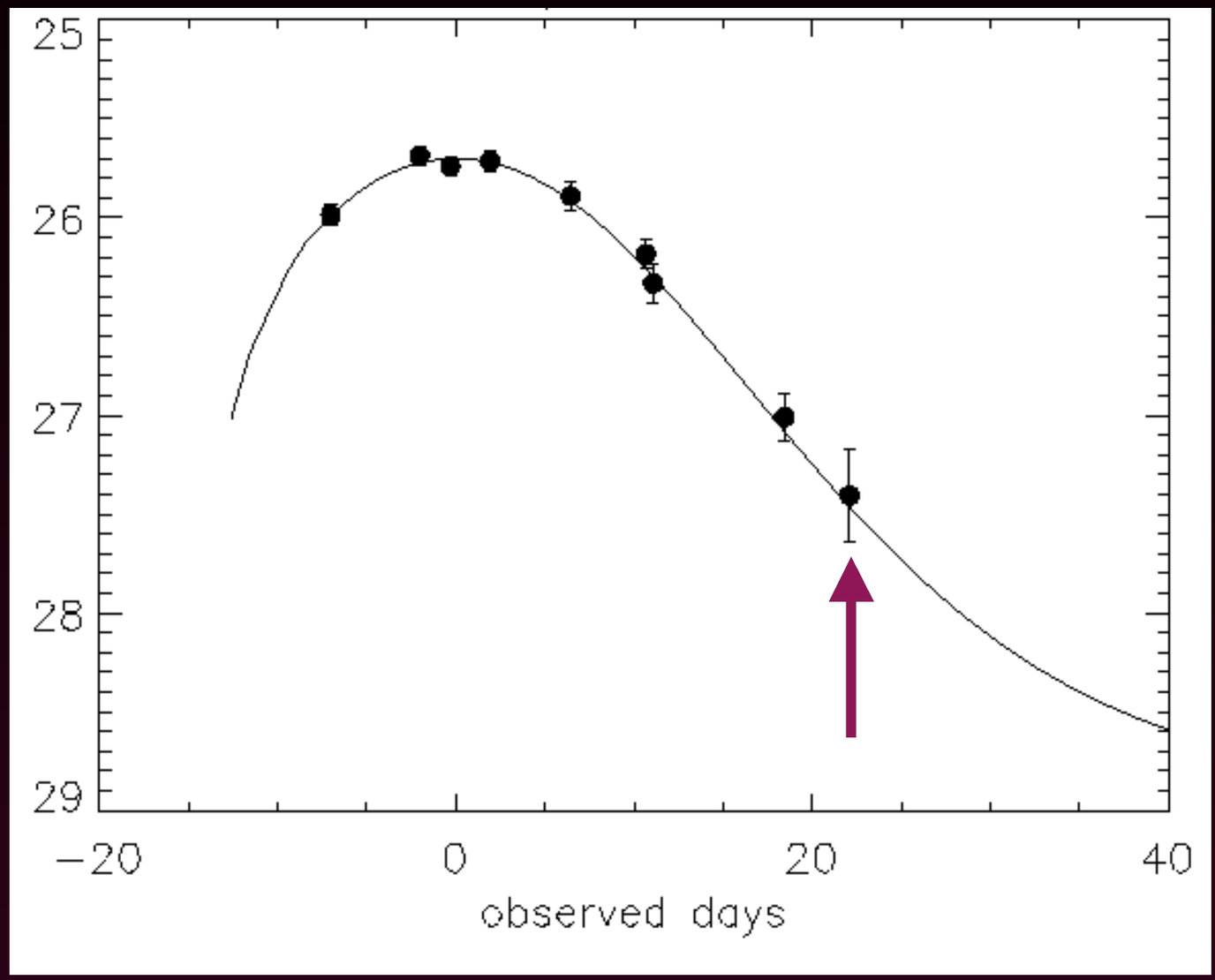
2002 November 17

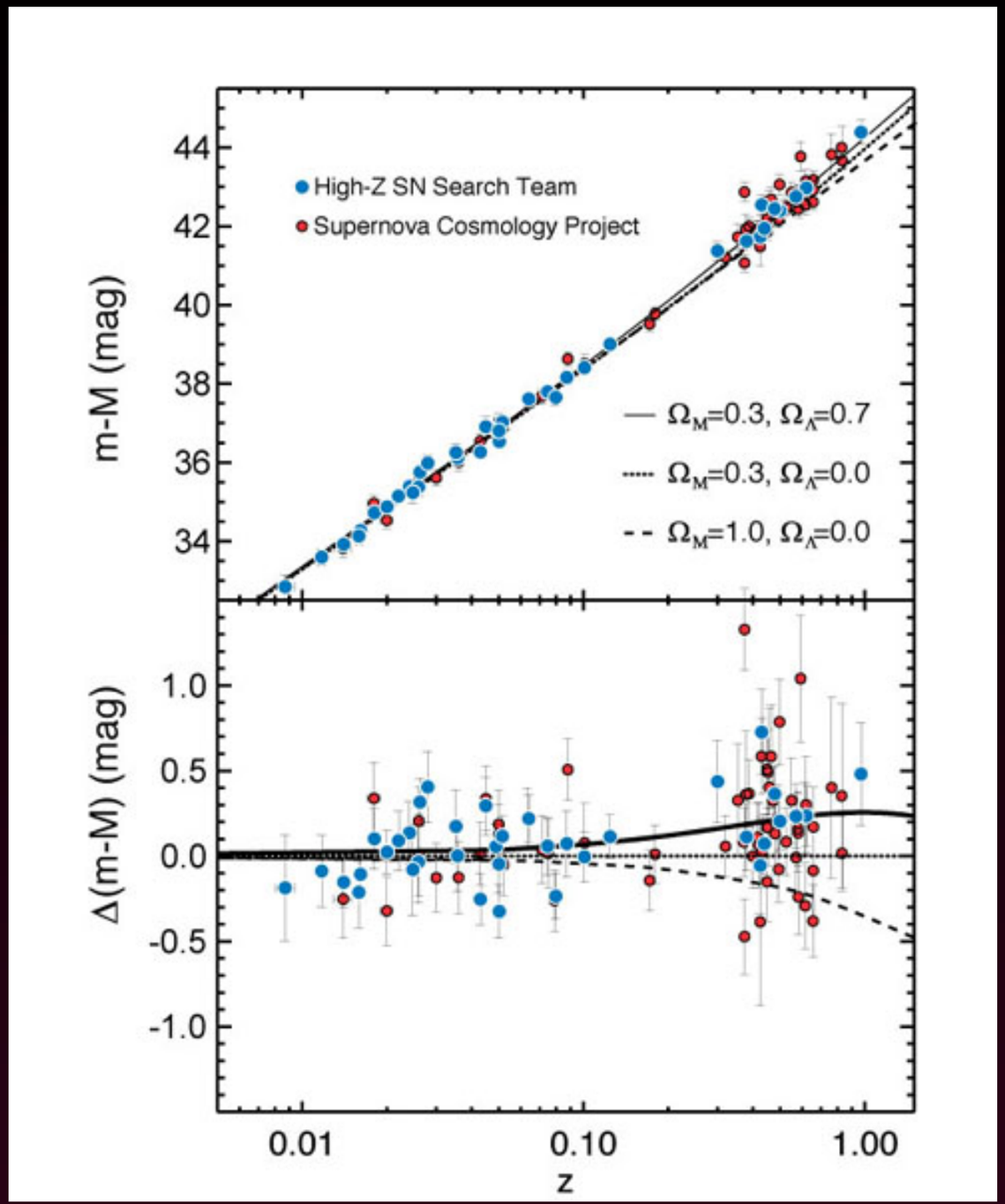


The Mighty Aphrodite

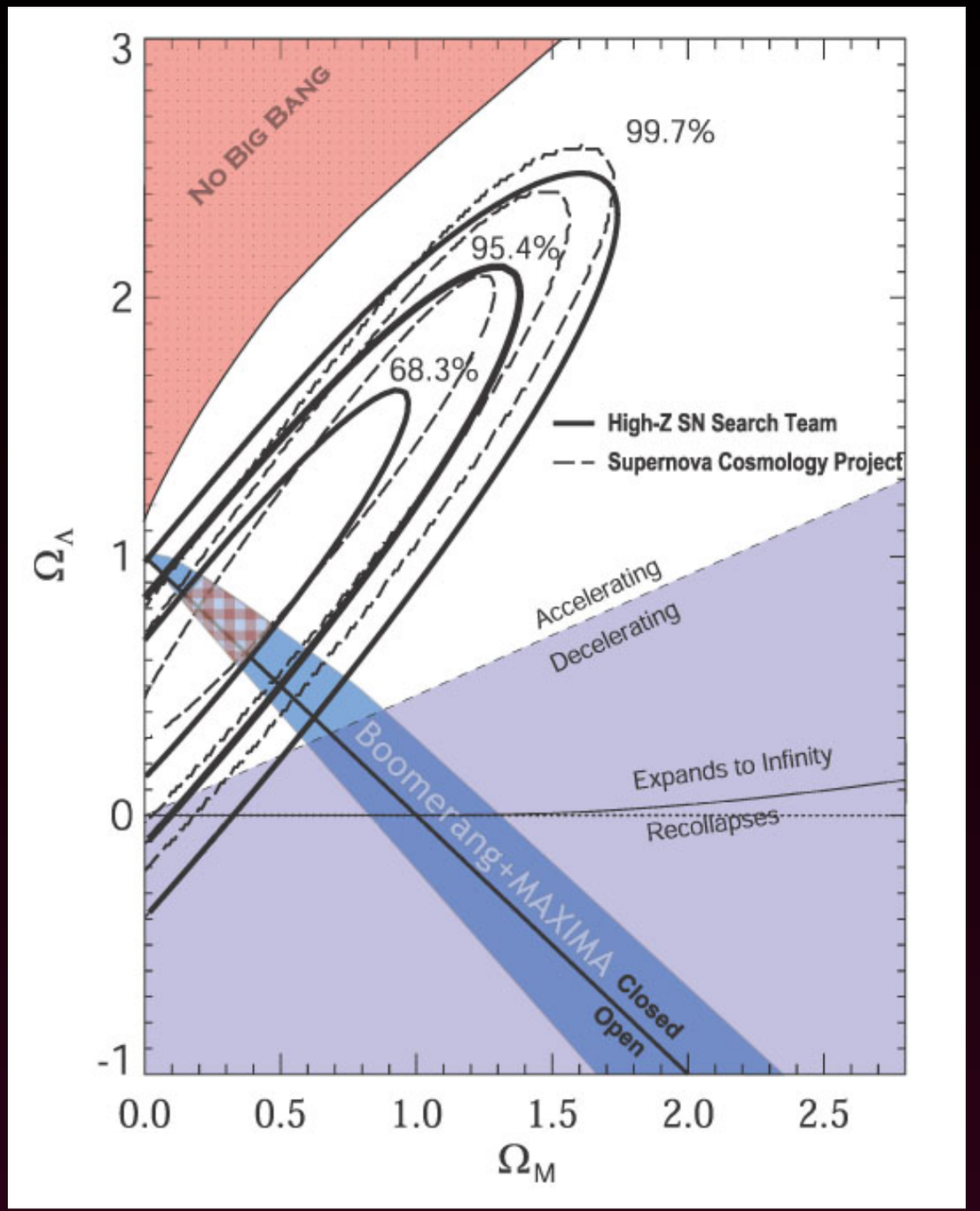
ACS z-band 1 orbit

2002 November 25





High-Z SN Search Team
Riess et al. (1998)



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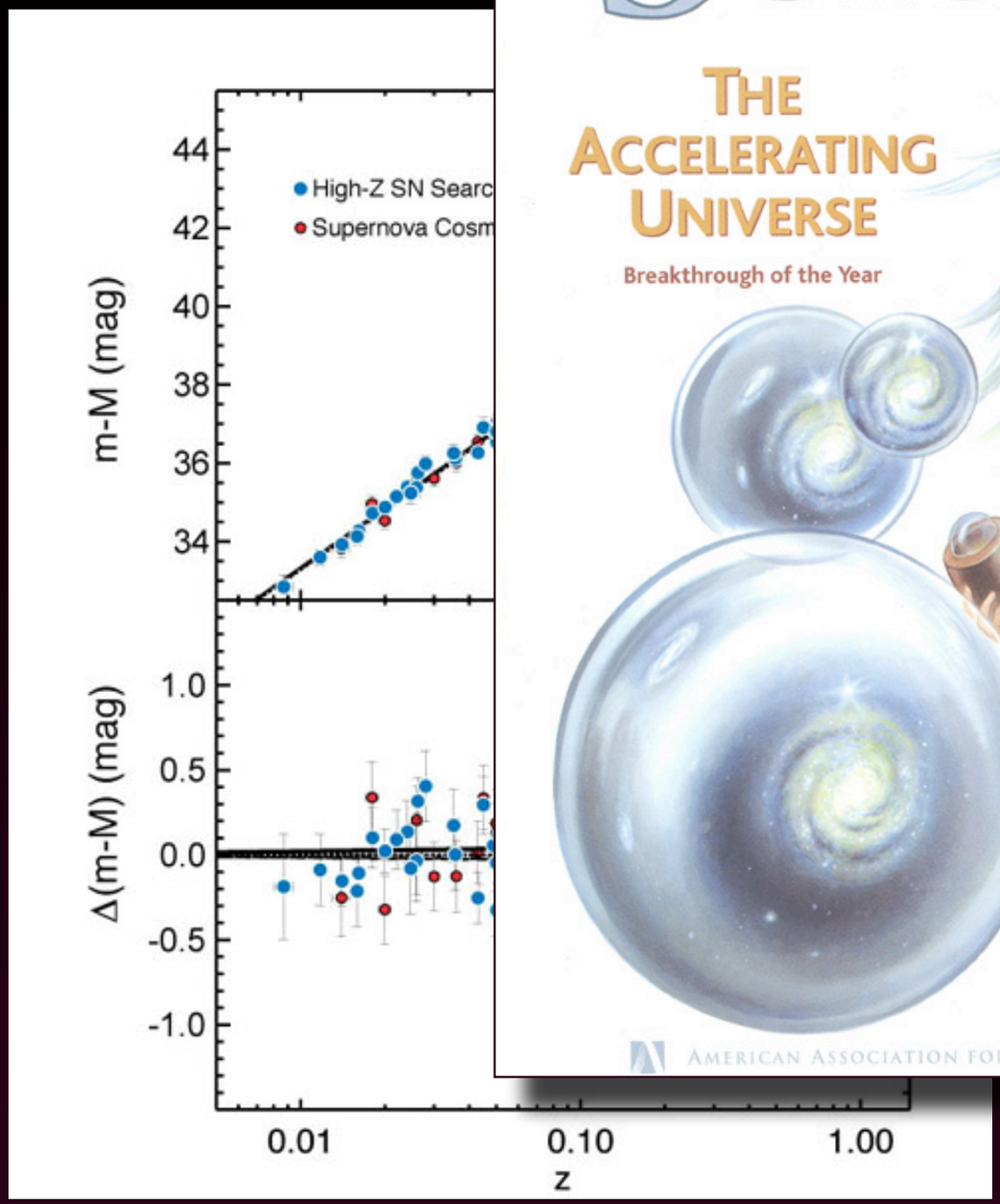

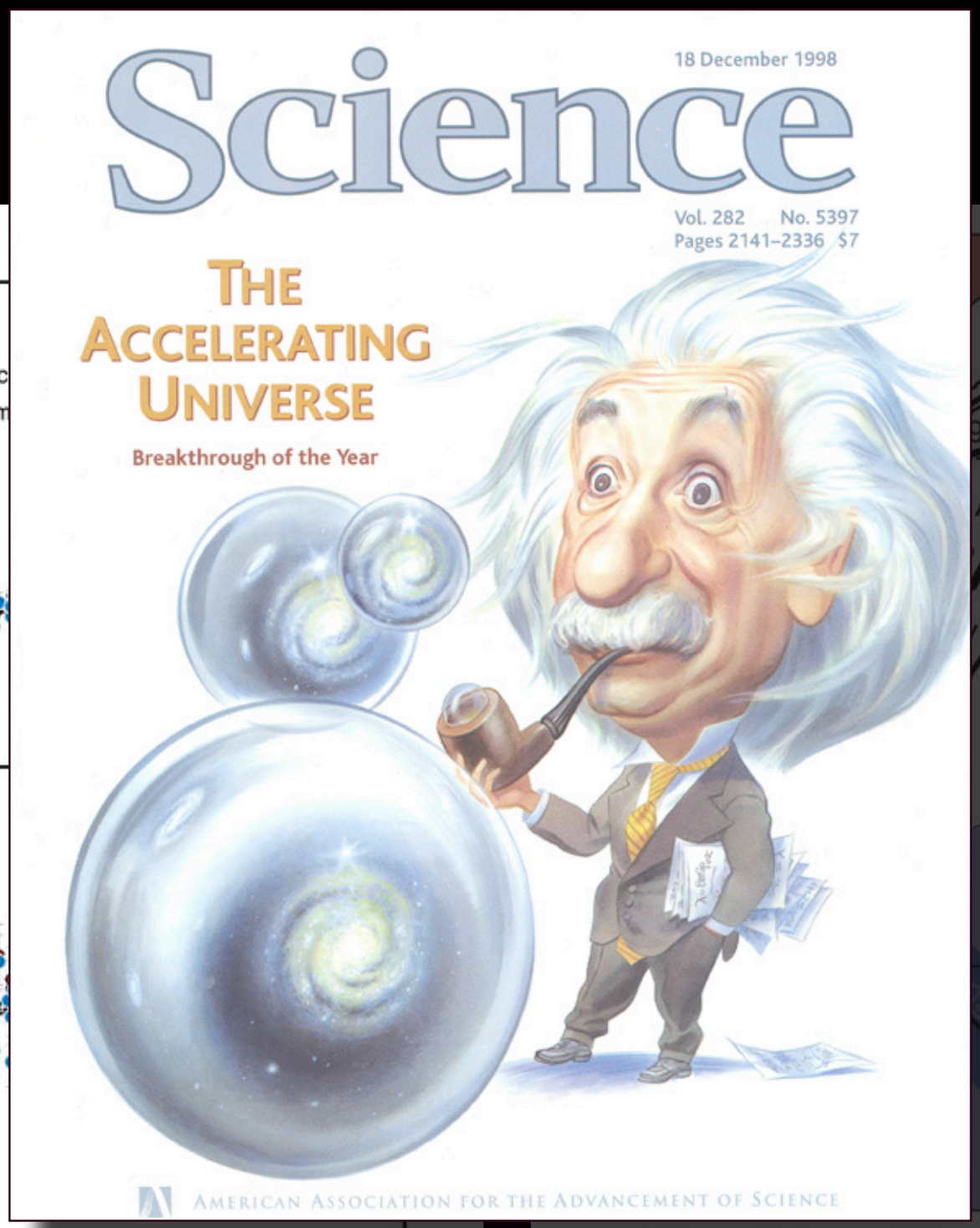

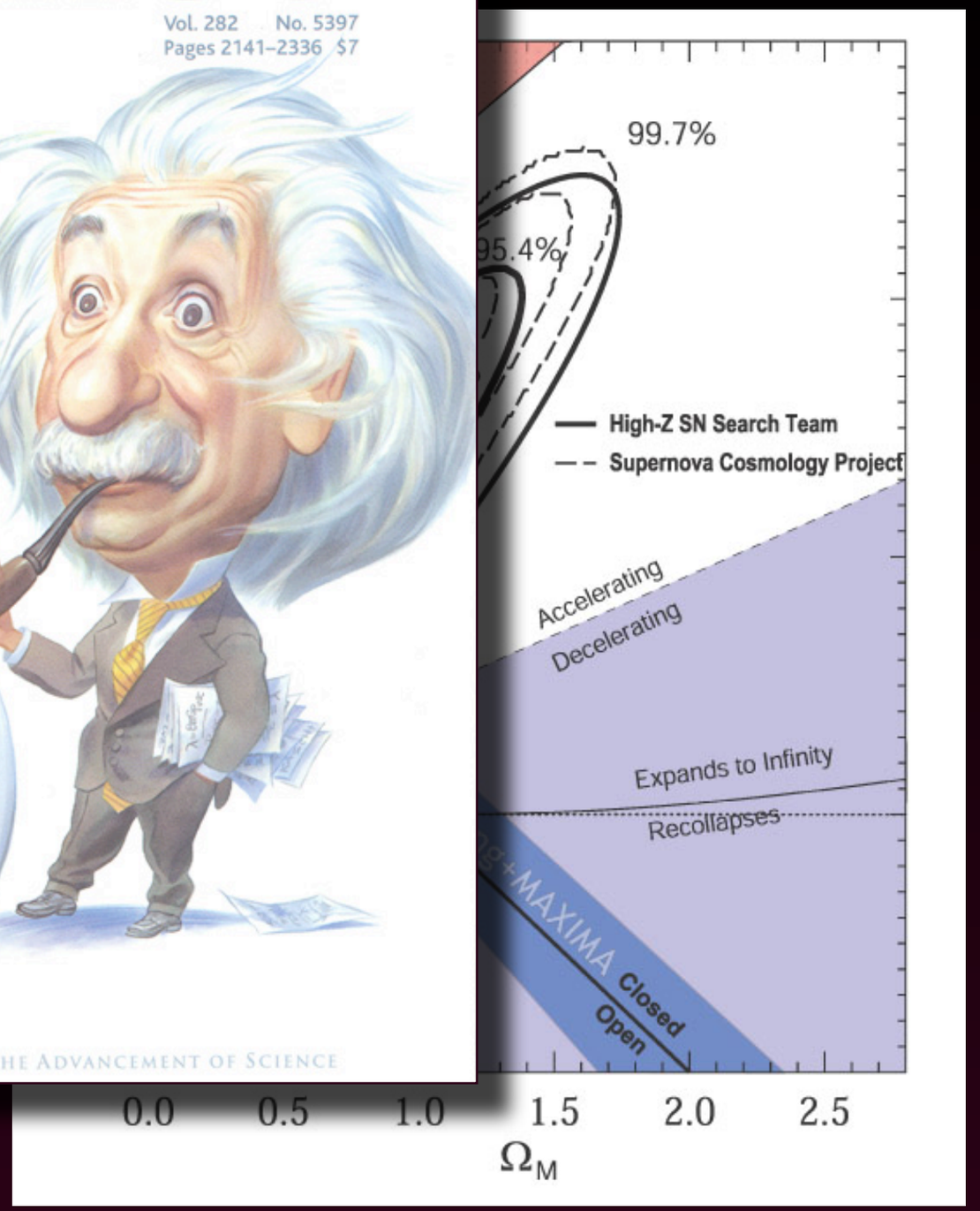

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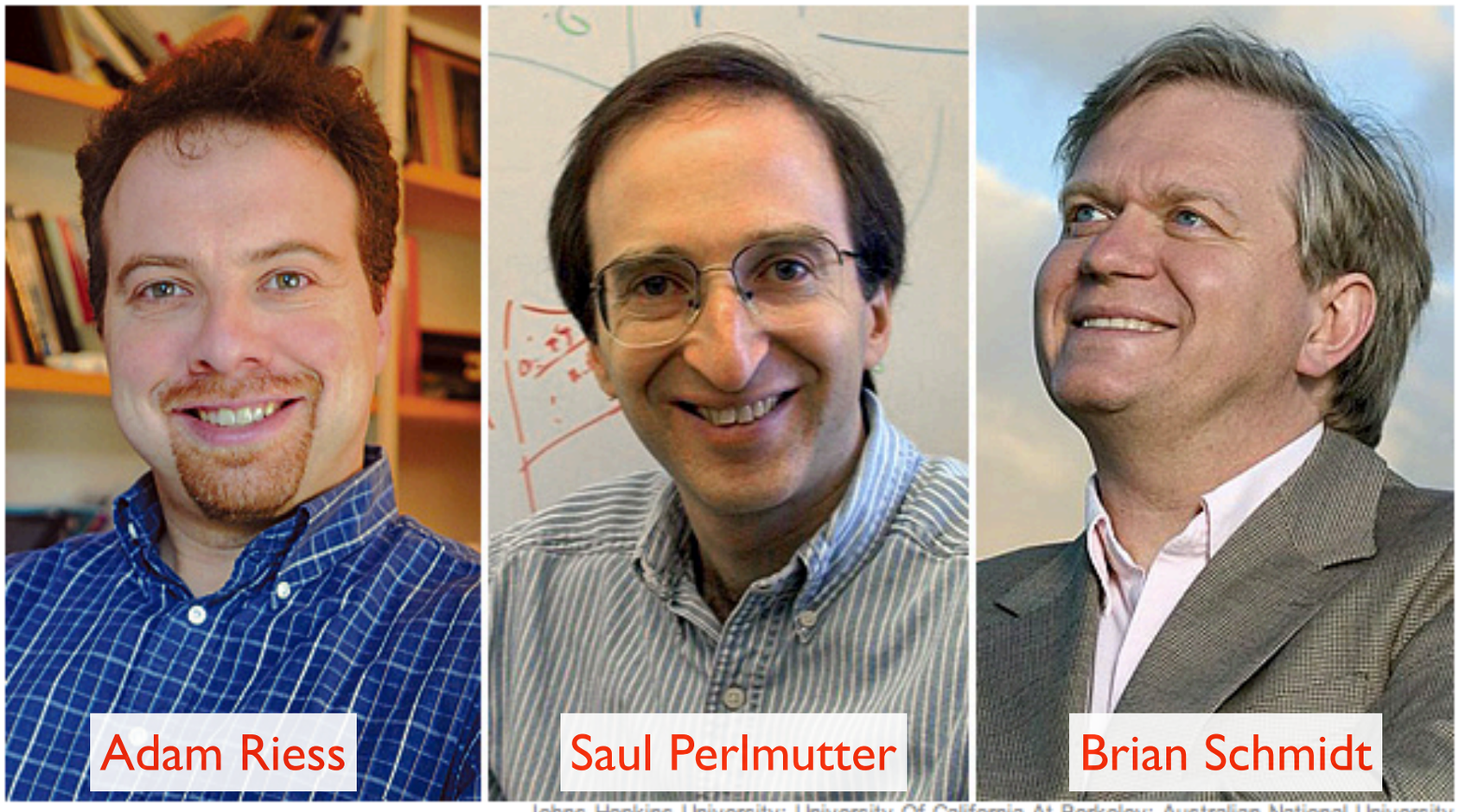
2011 Nobel Prize in Physics

Studies of Universe's Expansion Win Physics Nobel



Johns Hopkins University; University Of California At Berkeley; Australian National University

From left, Adam Riess, Saul Perlmutter and Brian Schmidt shared the Nobel Prize in physics awarded Tuesday.

from the New York Times

OBSERVATIONAL EVIDENCE FROM SUPERNOVAE FOR AN ACCELERATING UNIVERSE AND A COSMOLOGICAL CONSTANT

THE ASTRONOMICAL JOURNAL, 116:1009–1038, 1998 September

ADAM G. RIESS,[1] ALEXEI V. FILIPPENKO,[1] PETER CHALLIS,[2] ALEJANDRO CLOCCHIATTI,[3] ALAN DIERCKS,[4] PETER M. GARNAVICH,[2] RON L. GILLILAND,[5] CRAIG J. HOGAN,[4] SAURABH JHA,[2] ROBERT P. KIRSHNER,[2] B. LEIBUNDGUT,[6] M. M. PHILLIPS,[7] DAVID REISS,[4] BRIAN P. SCHMIDT,[8,9] ROBERT A. SCHOMMER,[7] R. CHRIS SMITH,[7,10] J. SPYROMILIO,[6] CHRISTOPHER STUBBS,[4] NICHOLAS B. SUNTZEFF,[7] AND JOHN TONRY[11]

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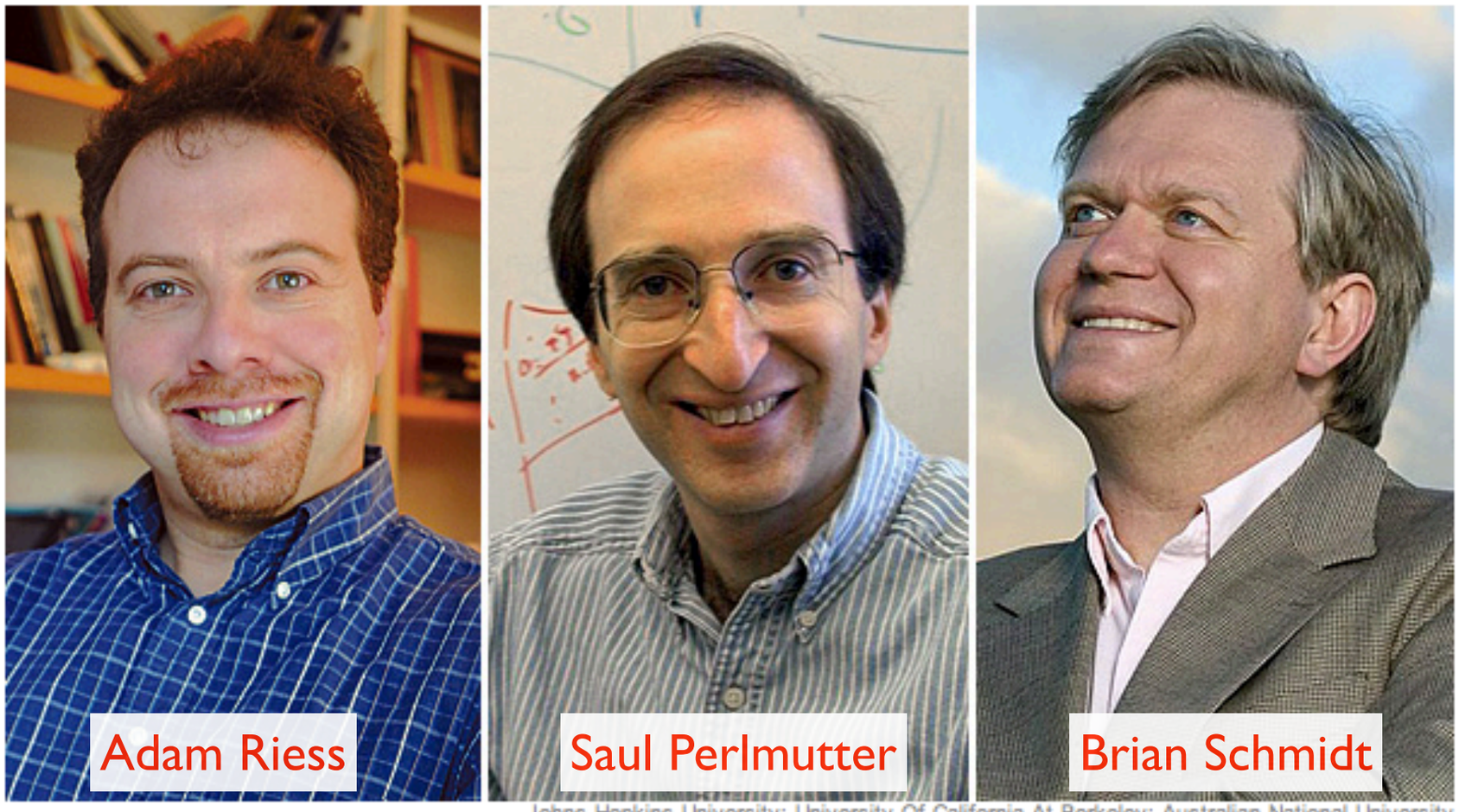

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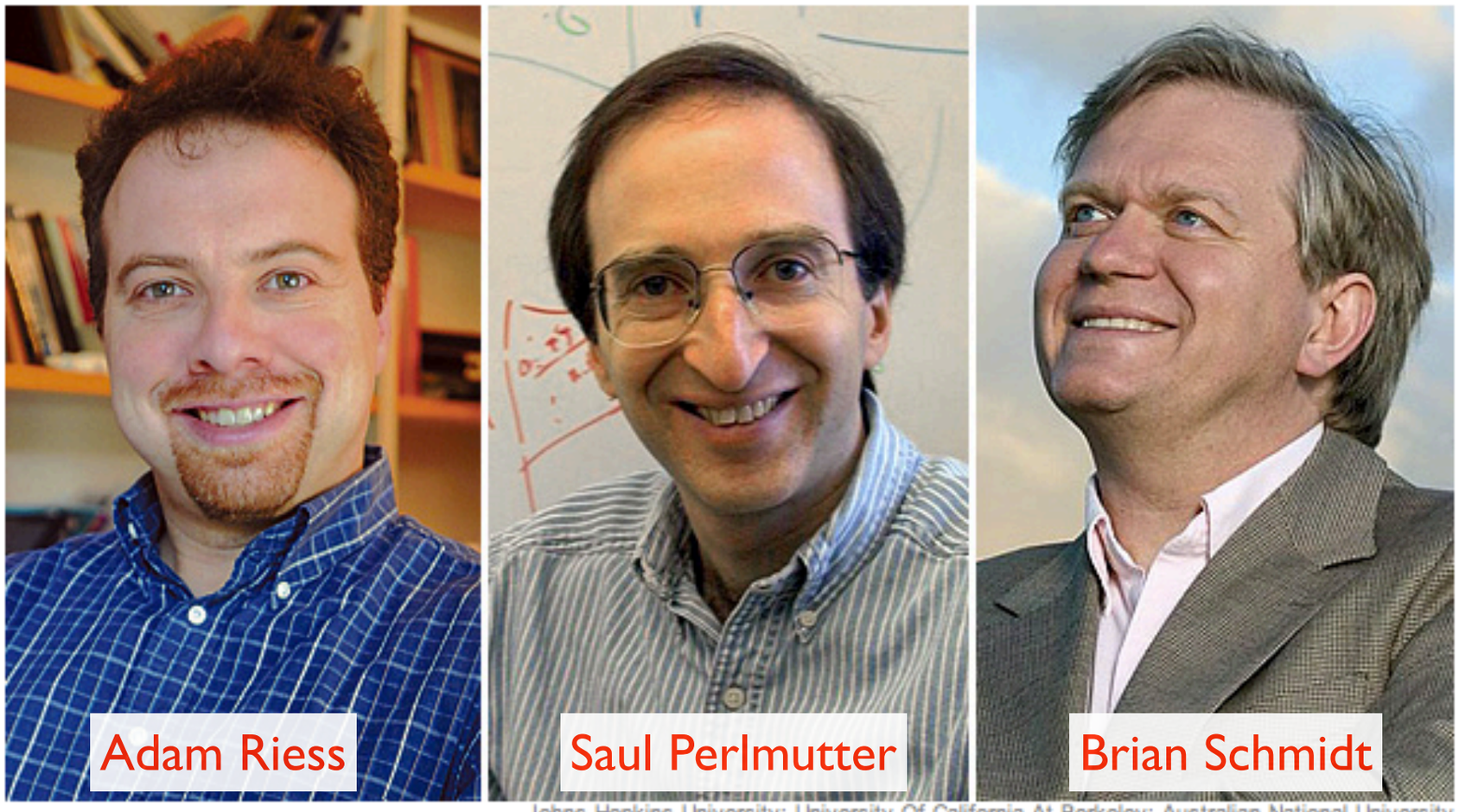

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Subject: ...2 shopping days left...

Wow!  Can't believe its almost here!
The Deadline (emphasis on "Dead")

That's right happy data reducers, only 2 days left
to turn in your completed relative SN photometry.
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a grad student's view
(from the trenches)

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Subject: many thanks

Dear Hard Workers,

Thanks to all who sent in their light curves yesterday!
I received everyone's except for one person (you know who you are)
and when they send their's in, I will have them all
(so "you know who you are" get moving).

Thanks Again to All -Adam

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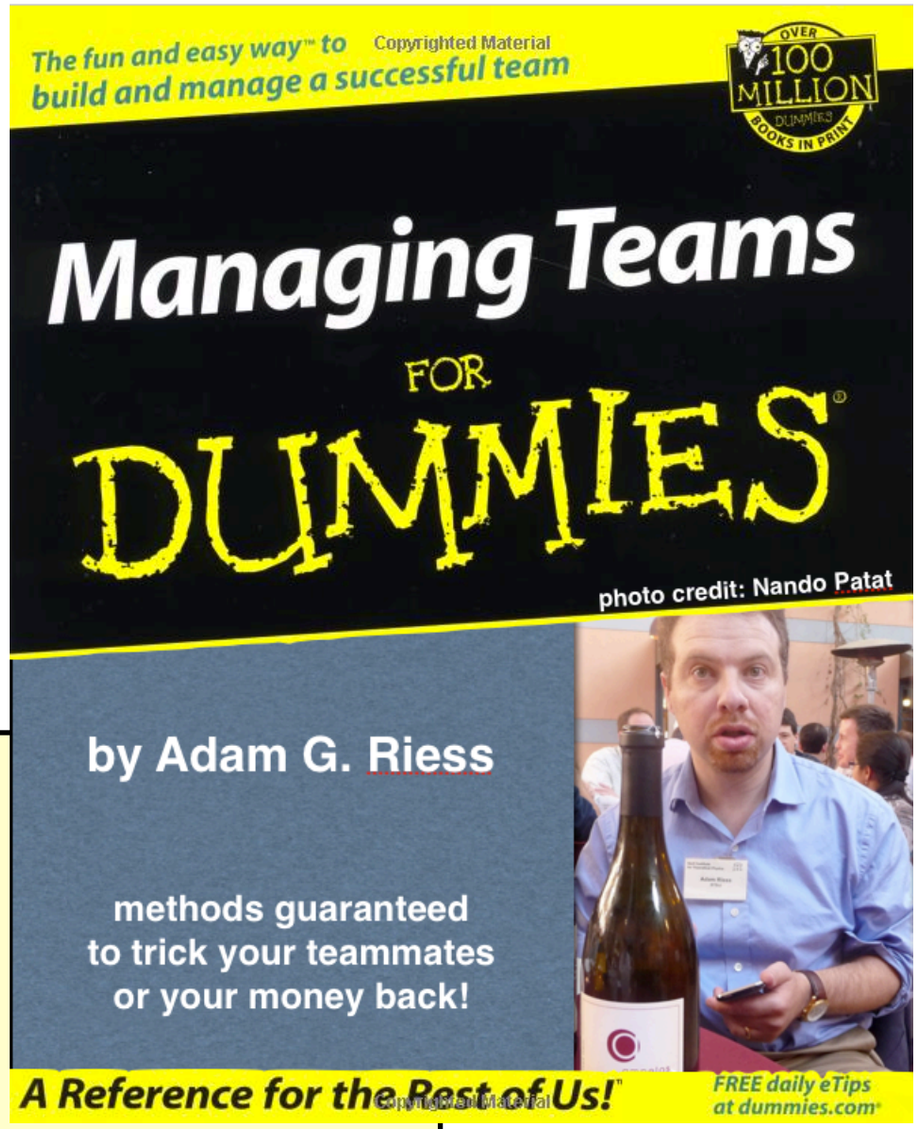

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moral: to win a Nobel Prize,
trick your students into working harder!

The Team is Excited, Worried (over 4 continents, email)…

A. Filippenko, Berkeley, CA, 1/10/1998 10:11am: "Adam showed me fantastic plots before he left for his wedding. Our data imply a non-zero cosmological constant! Who knows? This might be the right answer."

B. Leibundgut, Garching, Germany, 1/11/1998: 4:19am "Concerning a cosmological constant I'd like to ask Adam or anybody else in the group, if they feel prepared enough to defend the answer. There is no point in writing an article, if we are not very sure we are getting the right answer."

B. Schmidt, Australia, 1/11/1998: 7:13pm "I agree our data imply a cosmological constant, but how confident are we in this result? I find it very perplexing…."

R. Kirshner Santa Barbara, CA 1/12/1998 10:18am: "I am worried. In your heart you know [the cosmological constant] is wrong, though your head tells you that you don't care and you're just reporting the observations…It would be silly to say 'we MUST have a nonzero [cosmological constant]' only to retract it next year."

M. Phillips Chile, 1/12/1998, 04:56 am:"…As serious and responsible scientists (ha!), we all know that it is FAR TOO EARLY to be reaching firm conclusions about the value of the cosmological constant"

J. Tonry, Hawaii, 1/12/1998, 11:40 am:"…who remembers the detection of the magnetic monopole and other gaffs?…on the other hand, we should not be shy about getting our results out …"

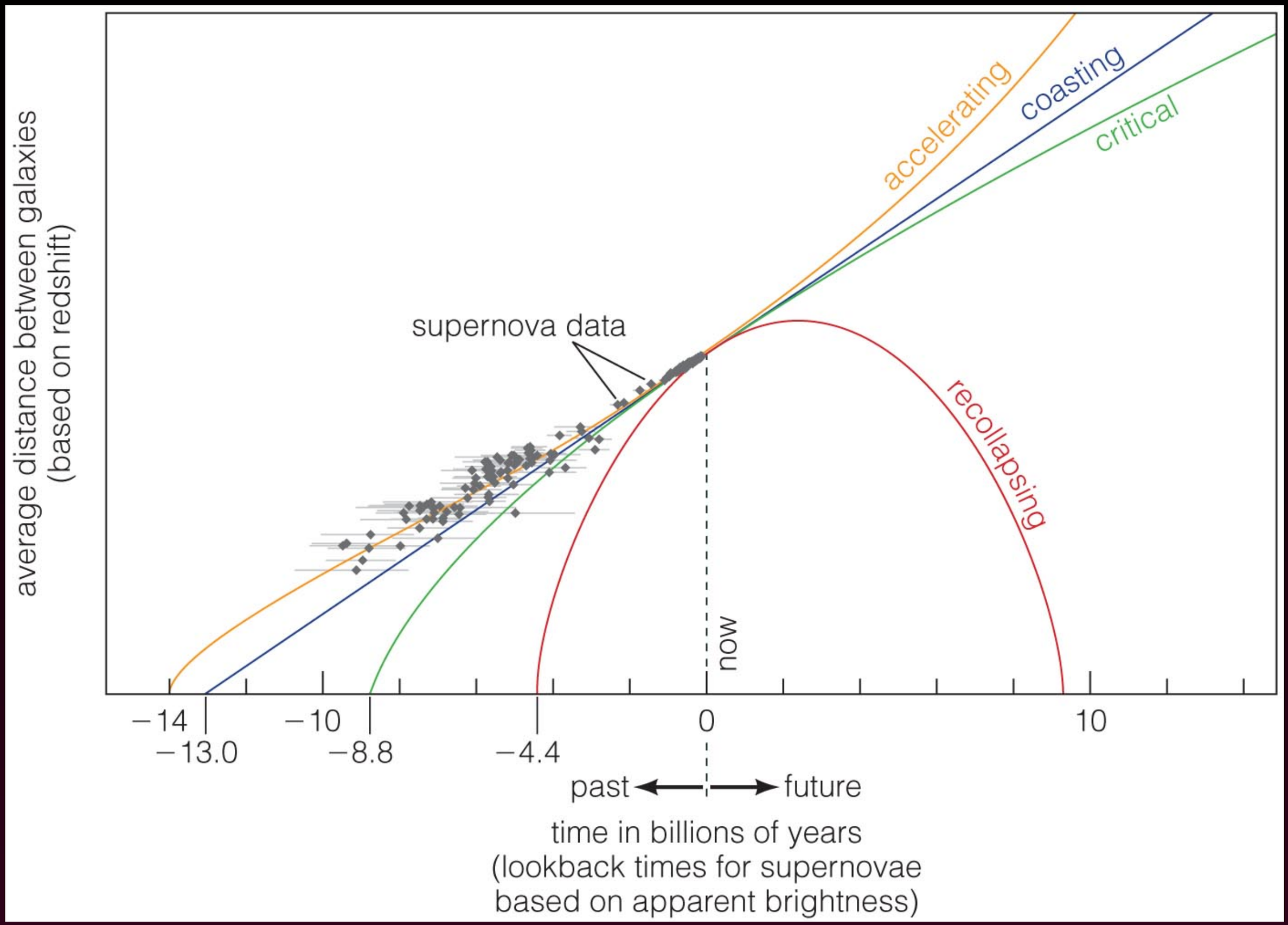
A. Filippenko 1/12/1998, 12:02 pm:"If we are wrong in the end, then so be it. At least we ran in the race."

A. Riess Berkeley, CA 1/12/1998 6:36pm: "The results are very surprising, shocking even. I have avoided telling anyone about them because I wanted to do some cross checks (I have) and I wanted to get further into writing the results up…The data require a nonzero cosmological constant! Approach these results not with your heart or head but with your eyes. We are observers after all!"

A. Clocchiatti, Chile 1/13/1998 07:30pm: "If Einstein made a mistake with the cosmological constant…Why couldn't we?"

N. Suntzeff Chile 1/13/1998 1:47pm: "I really encourage you [Adam] to work your butt off on this. We need to be careful…If you are really sure that the [cosmological constant] is not zero—my god, get it out! I mean this seriously—you probably never will have another scientific result that is more exciting come your way in your lifetime."

History and Future of the Expansion



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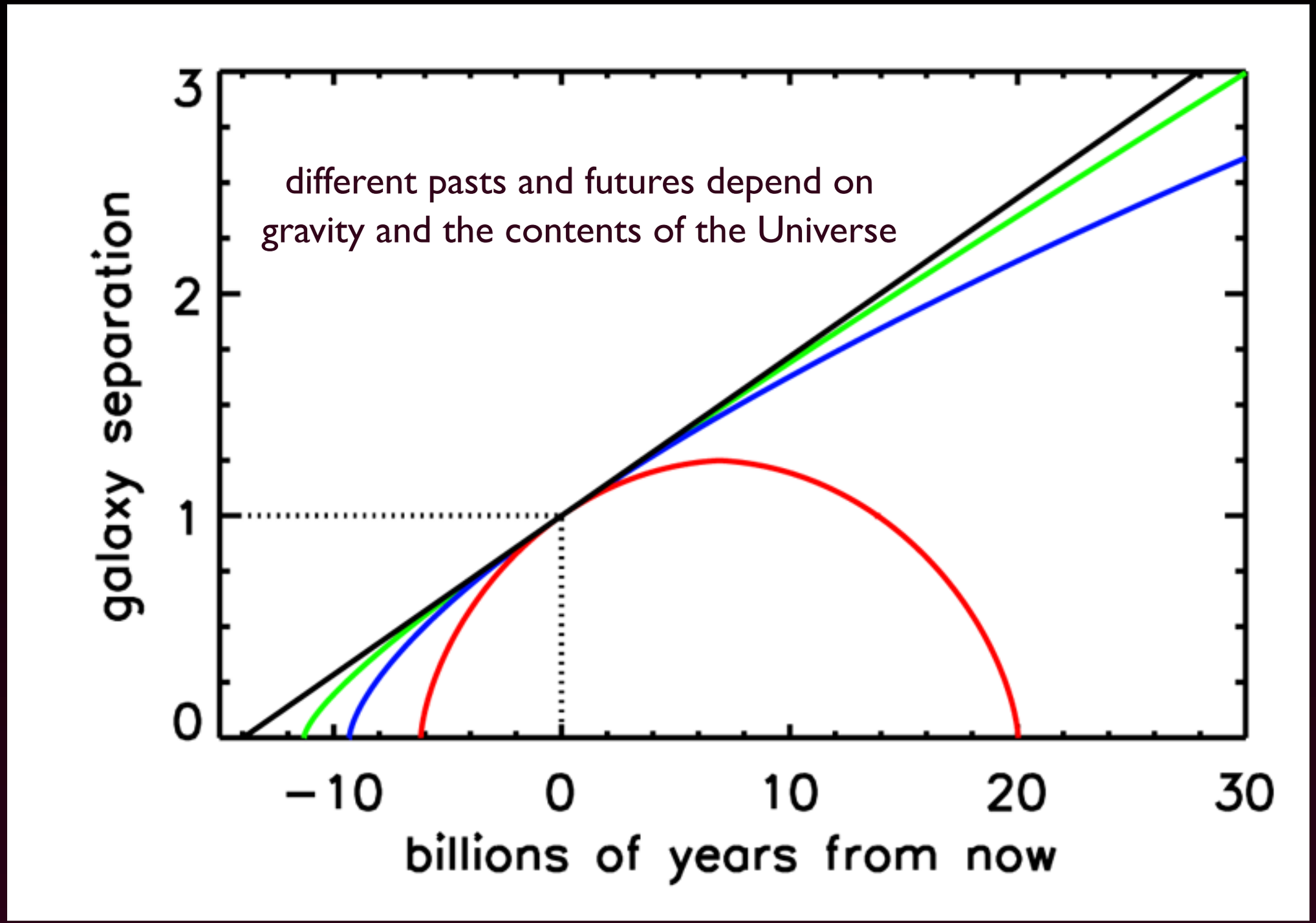

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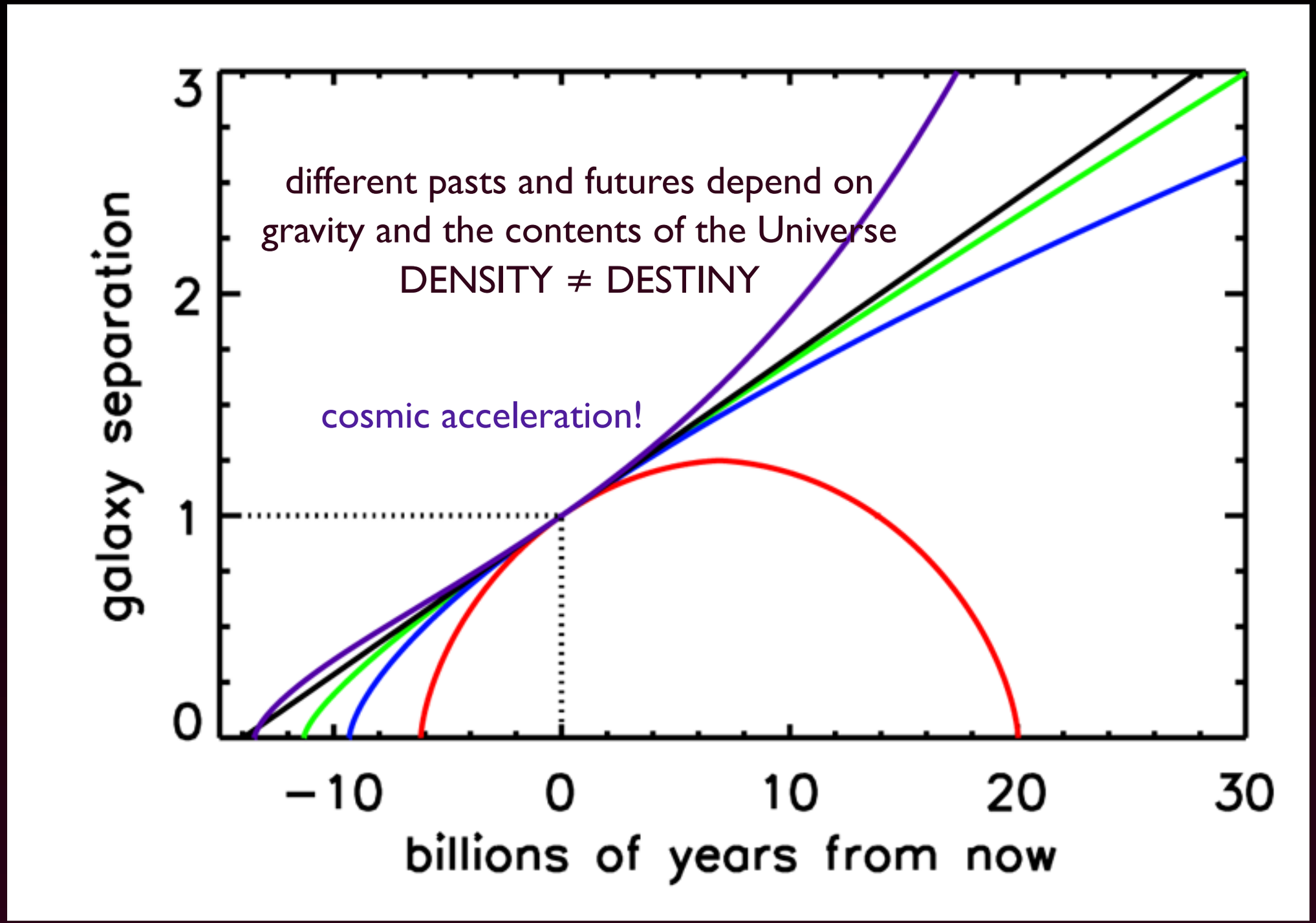
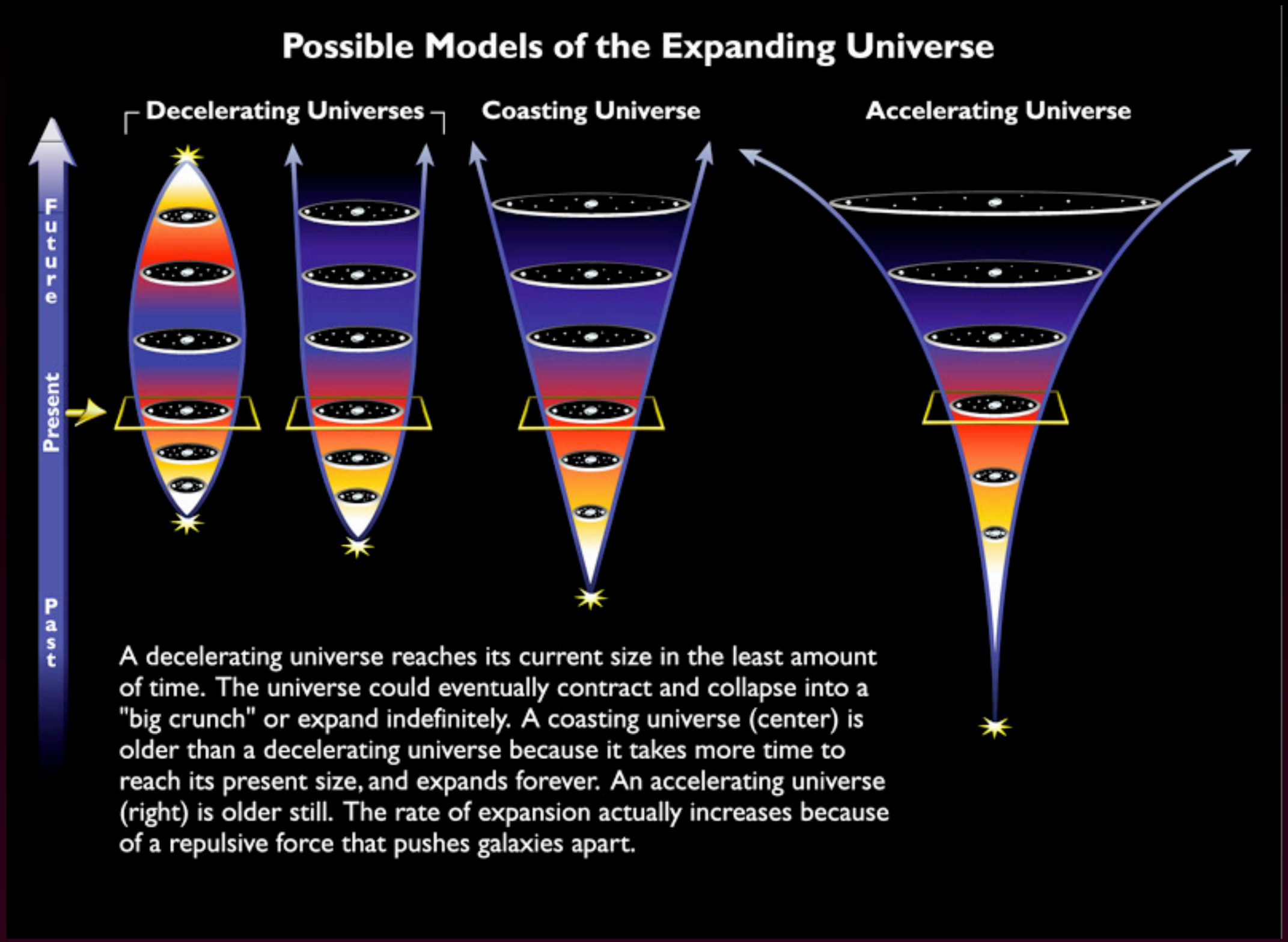


the High-Z SN Search Team
Stockholm, December 10th 2011

"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

The Accelerating Universe



from http://www.hubblesite.org

The Accelerating Universe

The Accelerating Universe

so what causes cosmic acceleration?

What Causes Cosmic Acceleration?

What Causes Cosmic Acceleration?

dark energy!

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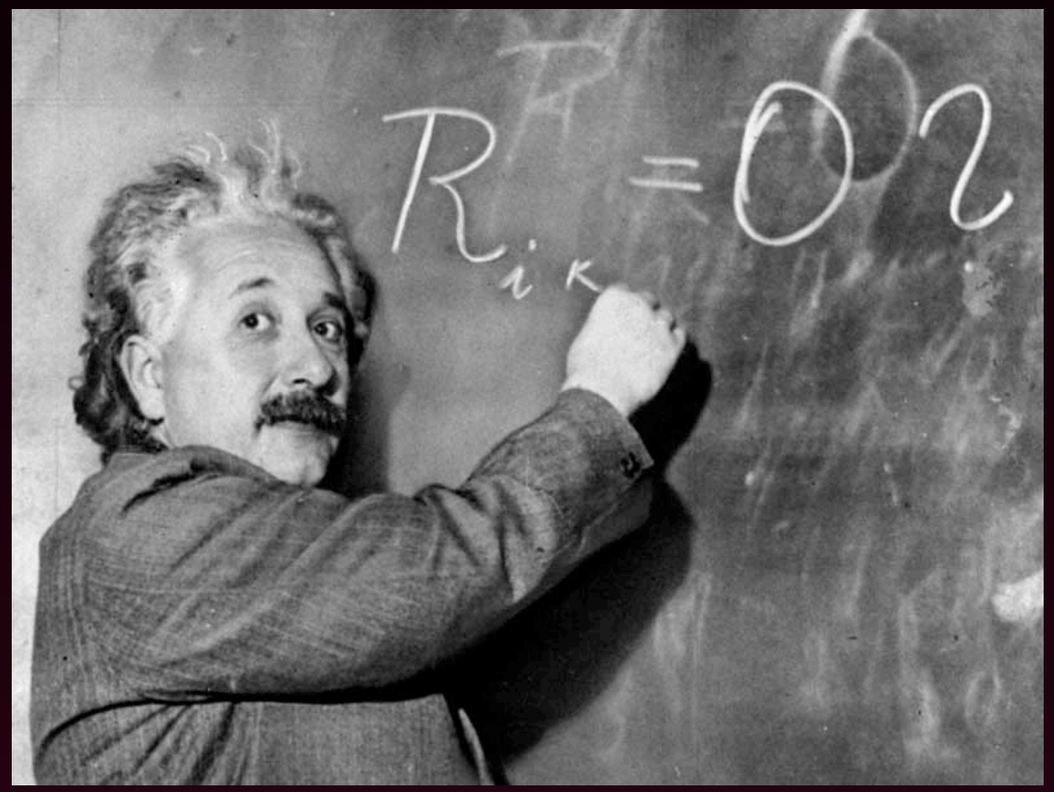

the cosmological constant?

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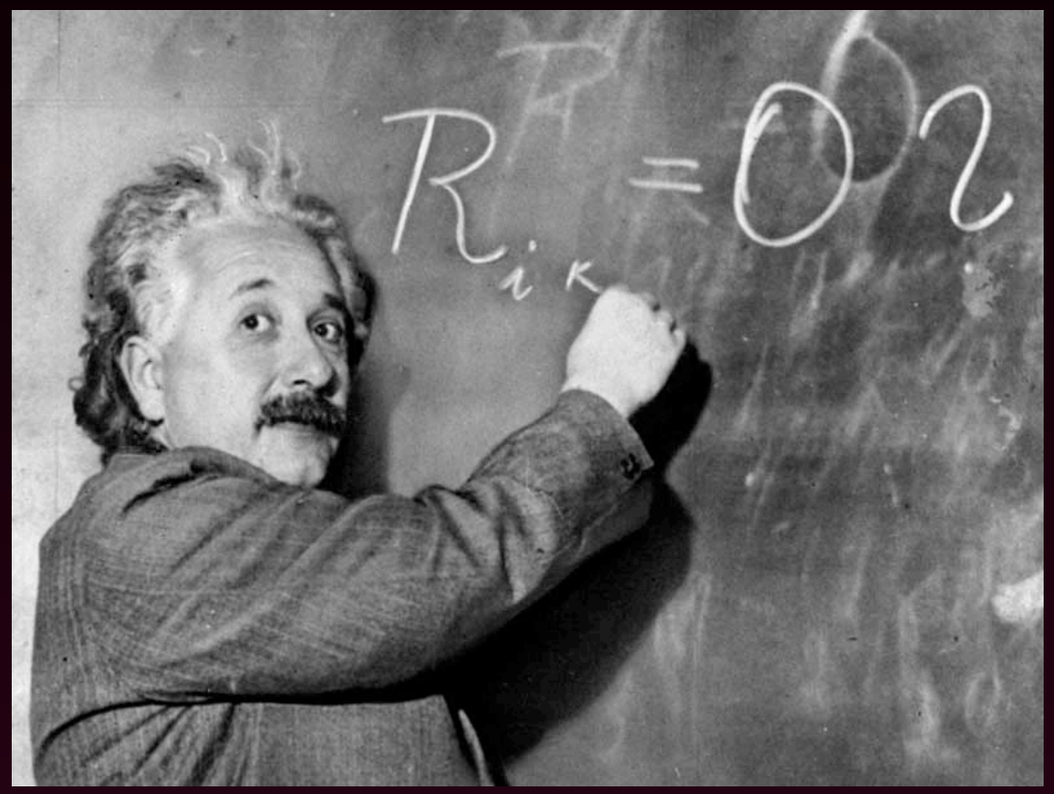


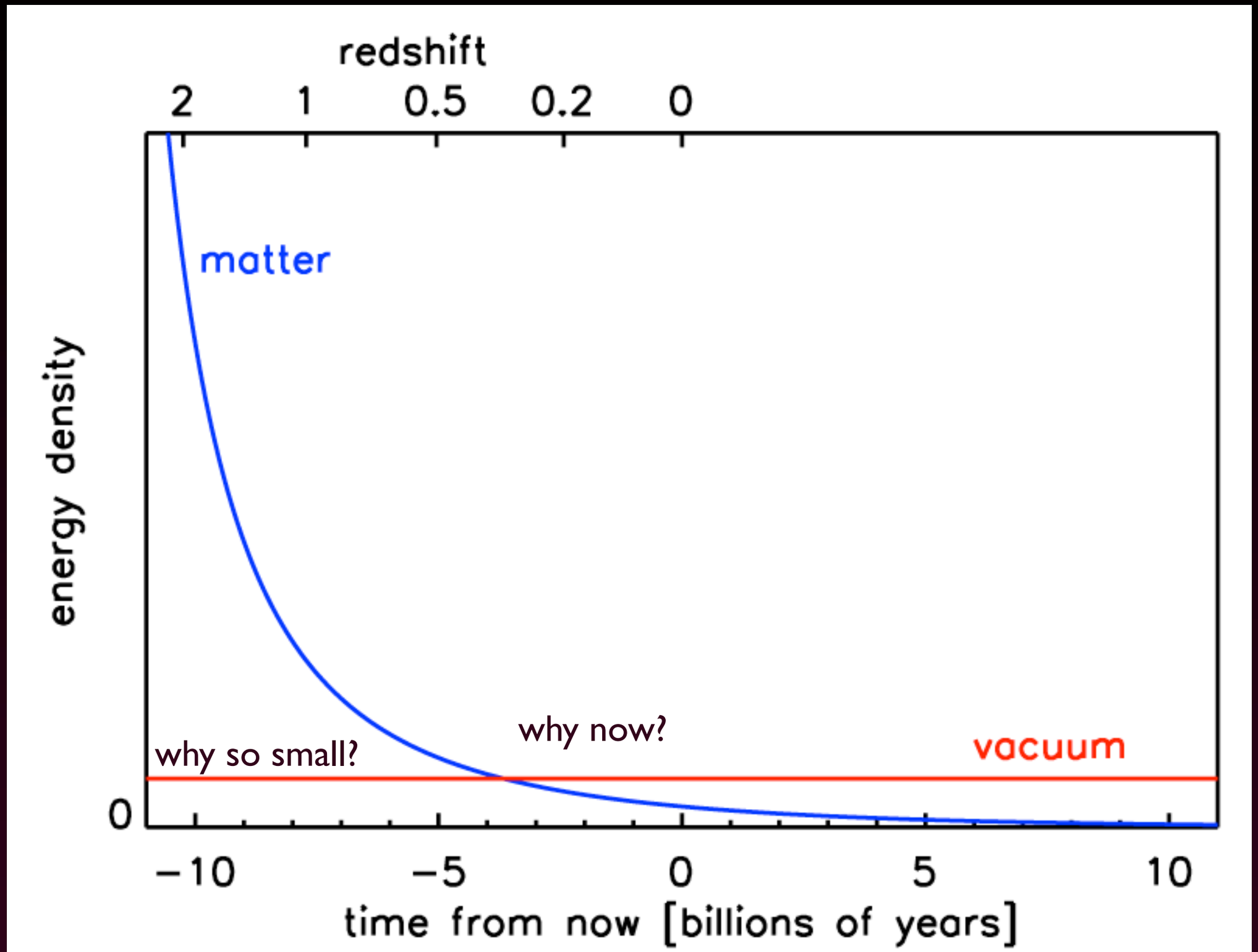
the cosmological constant?

quintessence?

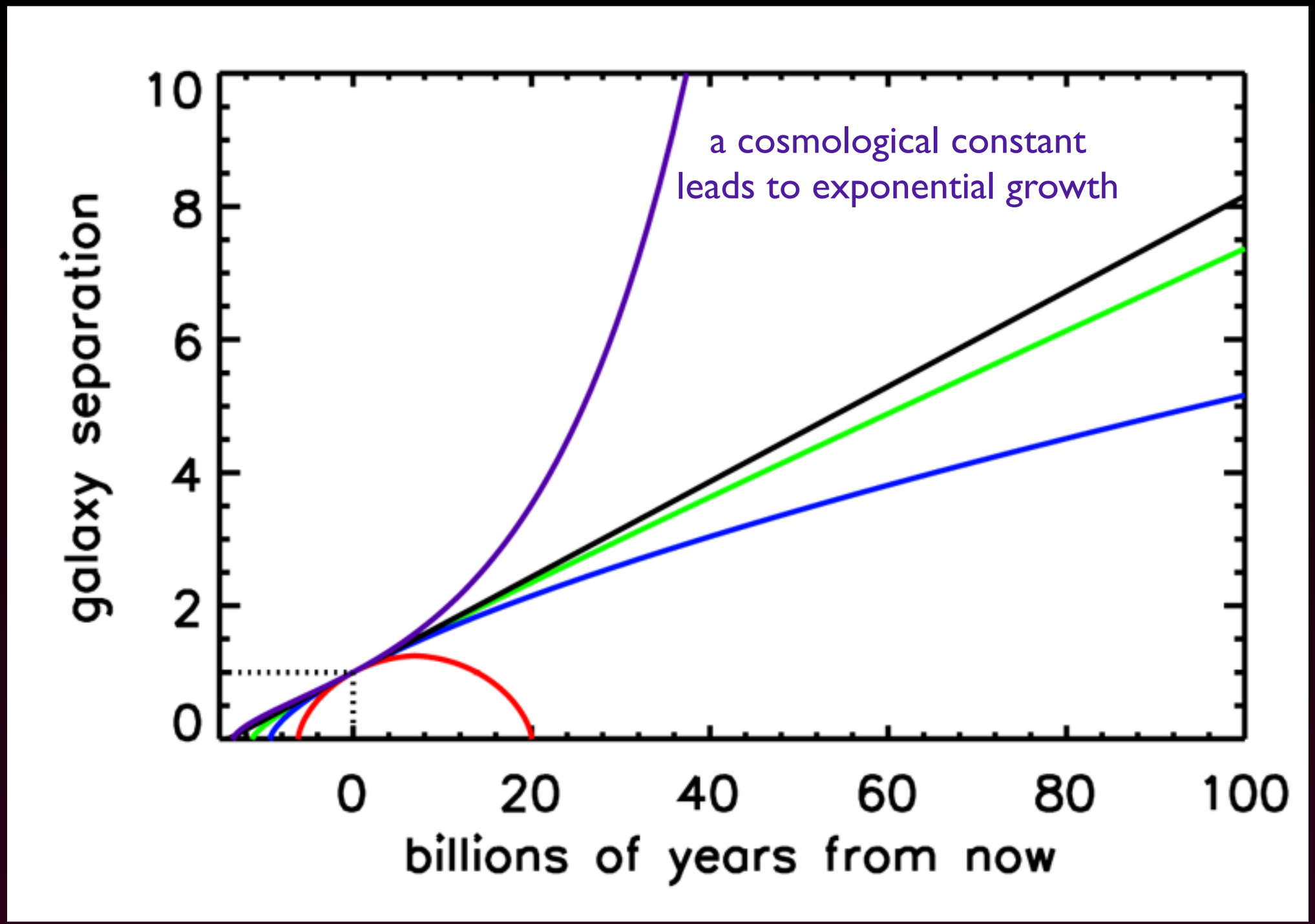
other dimensions?

modifications to general relativity?

Things that Concern Theorists

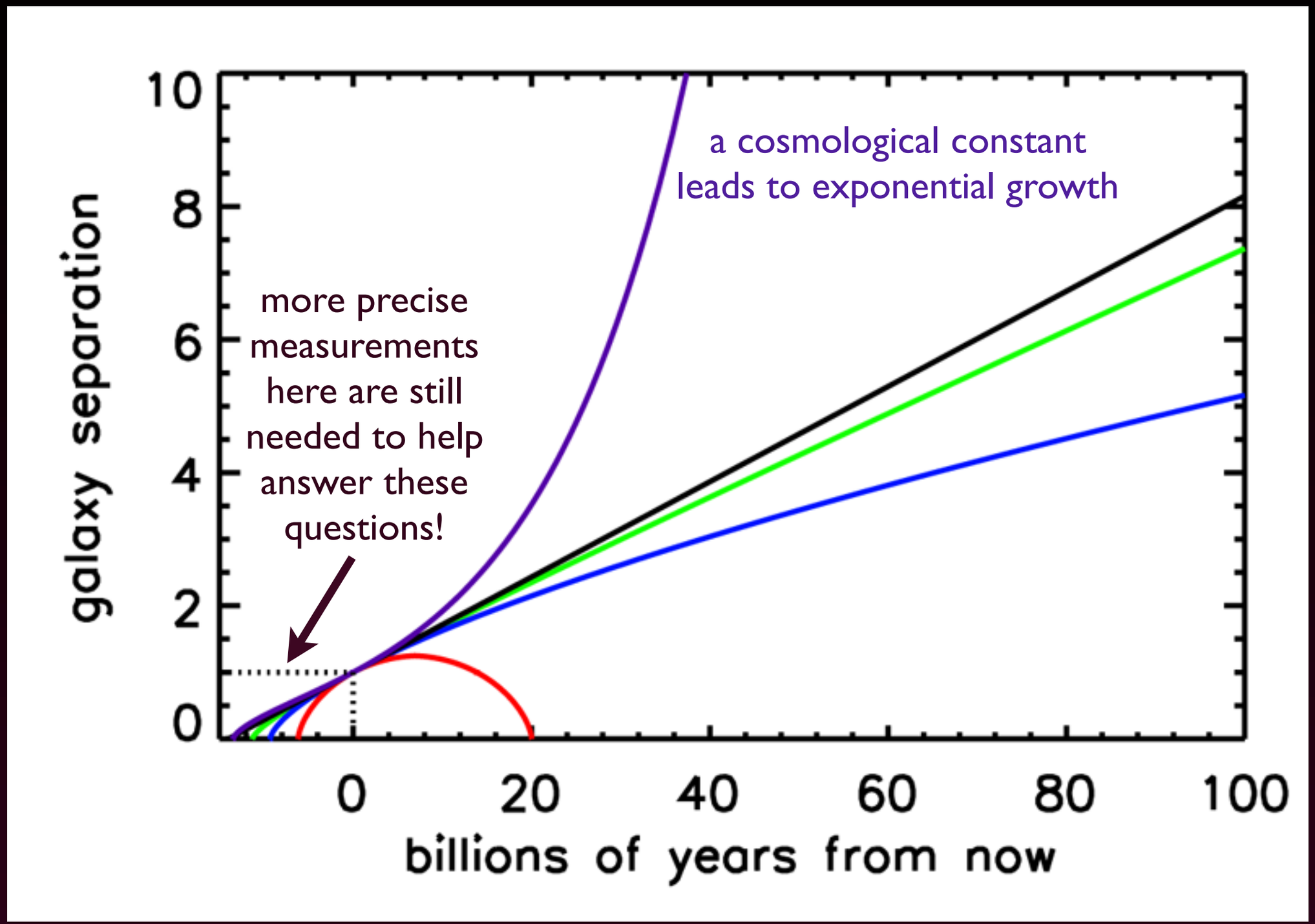


A Bleak Future? Maybe, Maybe Not



but dynamic dark energy means many outcomes are possible, including a Big Crunch (recollapse) or a Big Rip (in finite time)

A Bleak Future? Maybe, Maybe Not



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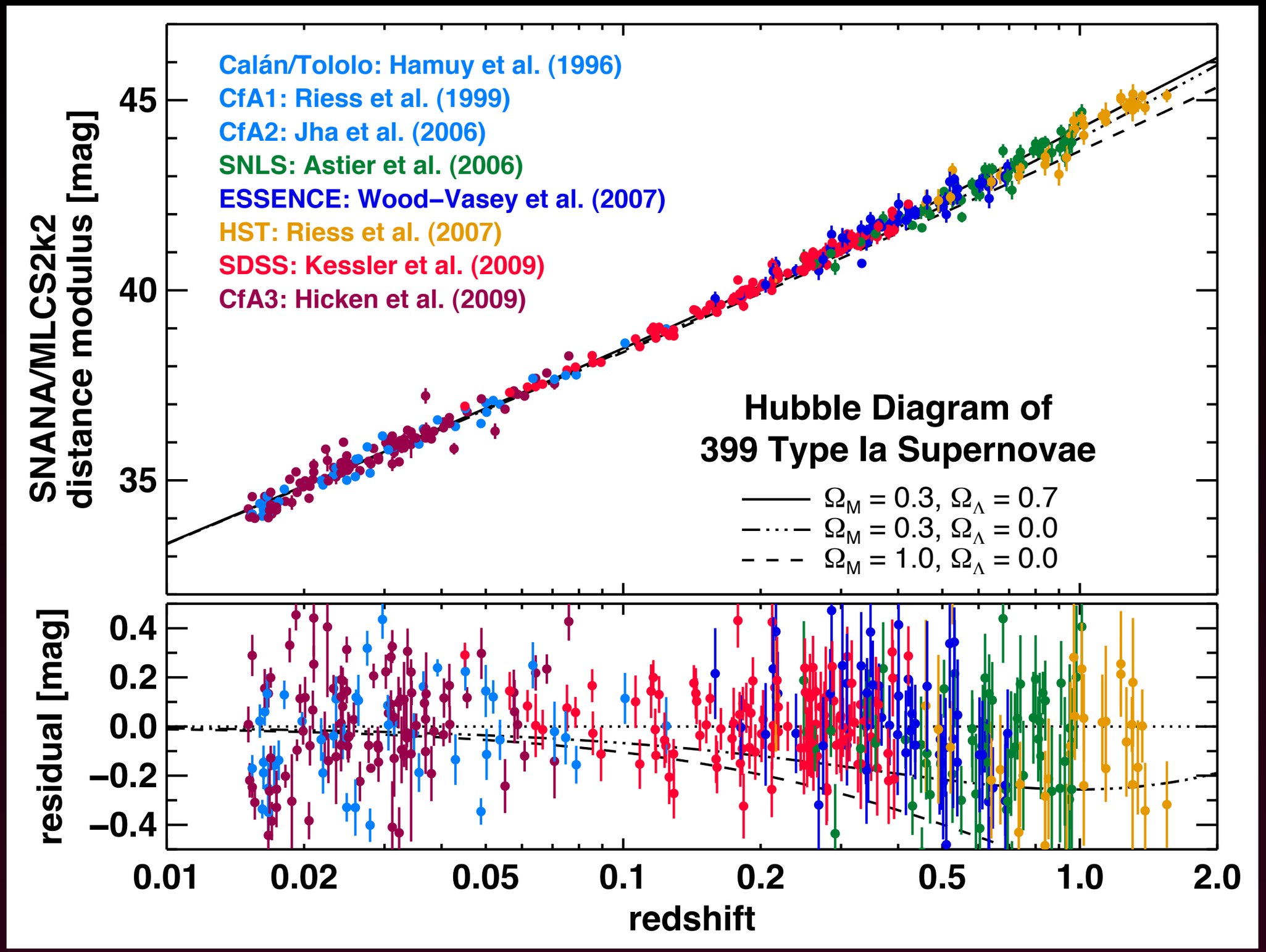
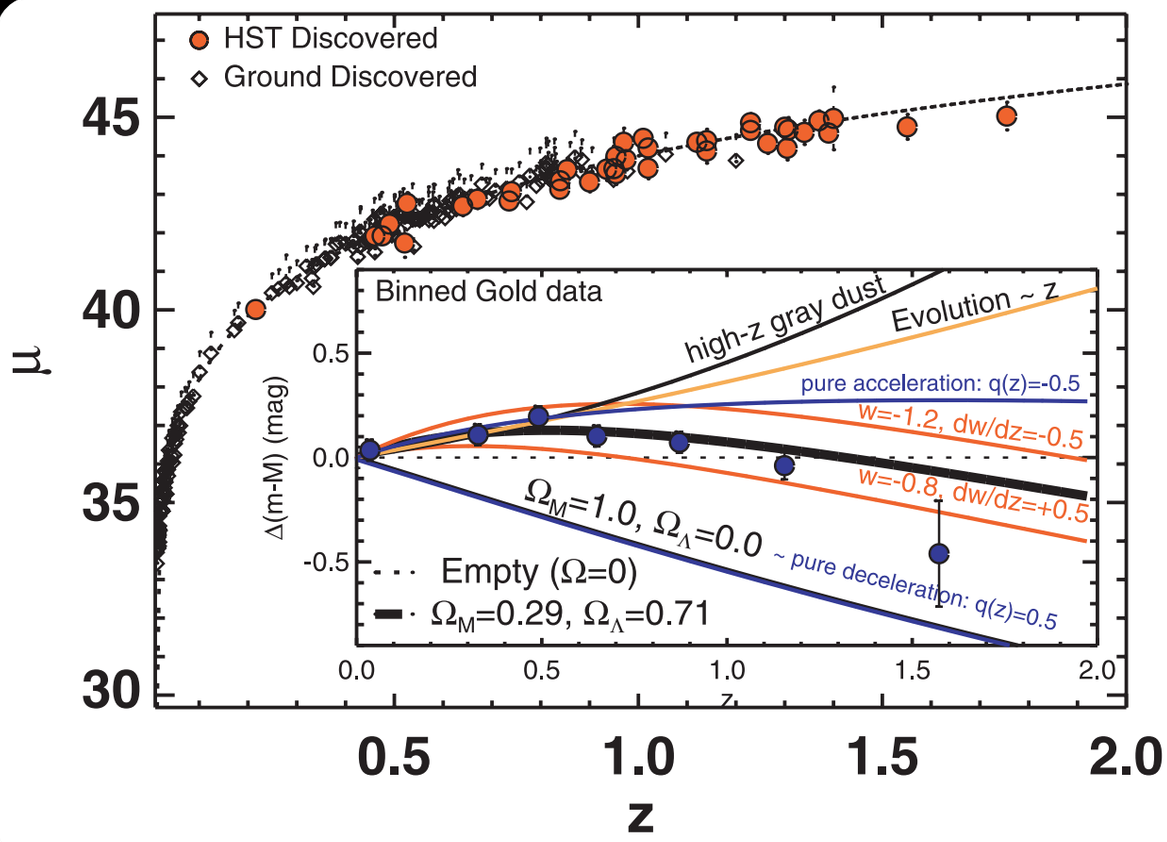
SN Ia Hubble Diagram

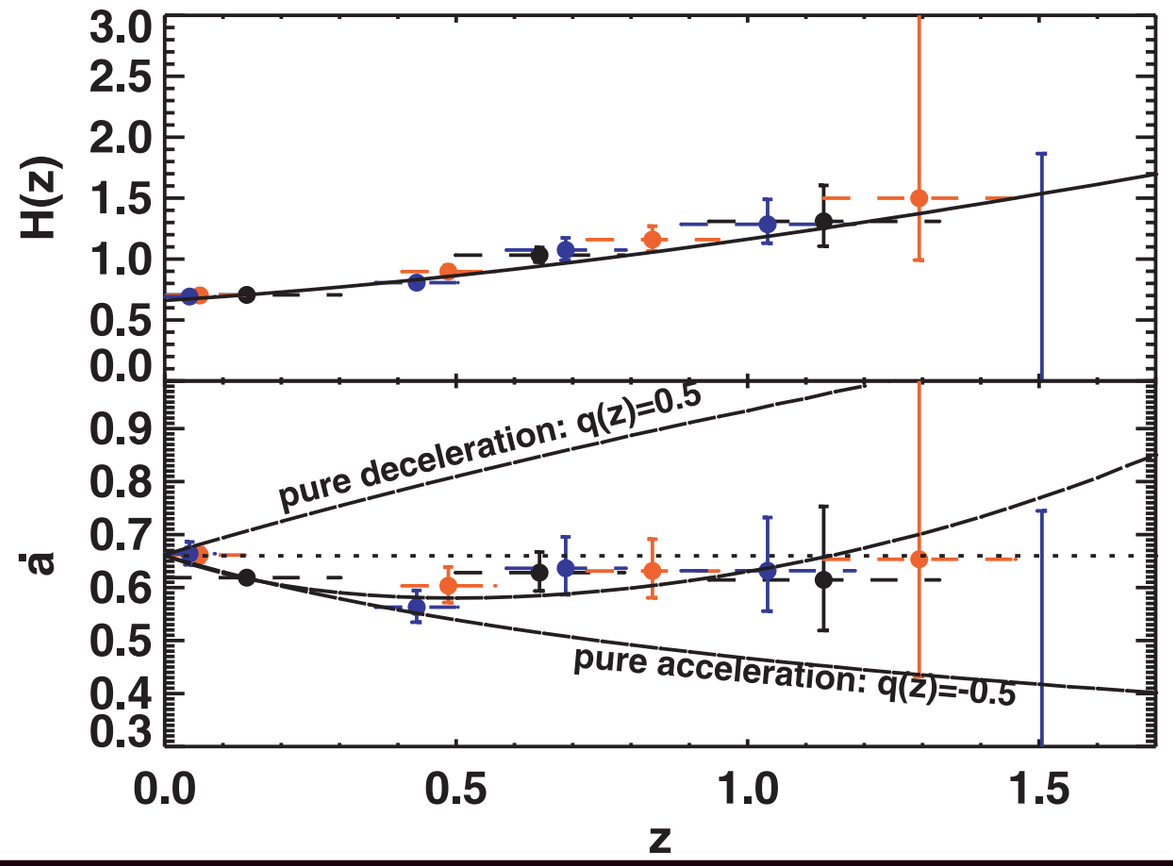


for the first time we have a continuous
expansion history measured from SN to z > 1

The Epoch of Deceleration

Riess et al. (2007)





HST-discovered supernovae at very high redshift show the Universe *decelerated* before the current acceleration

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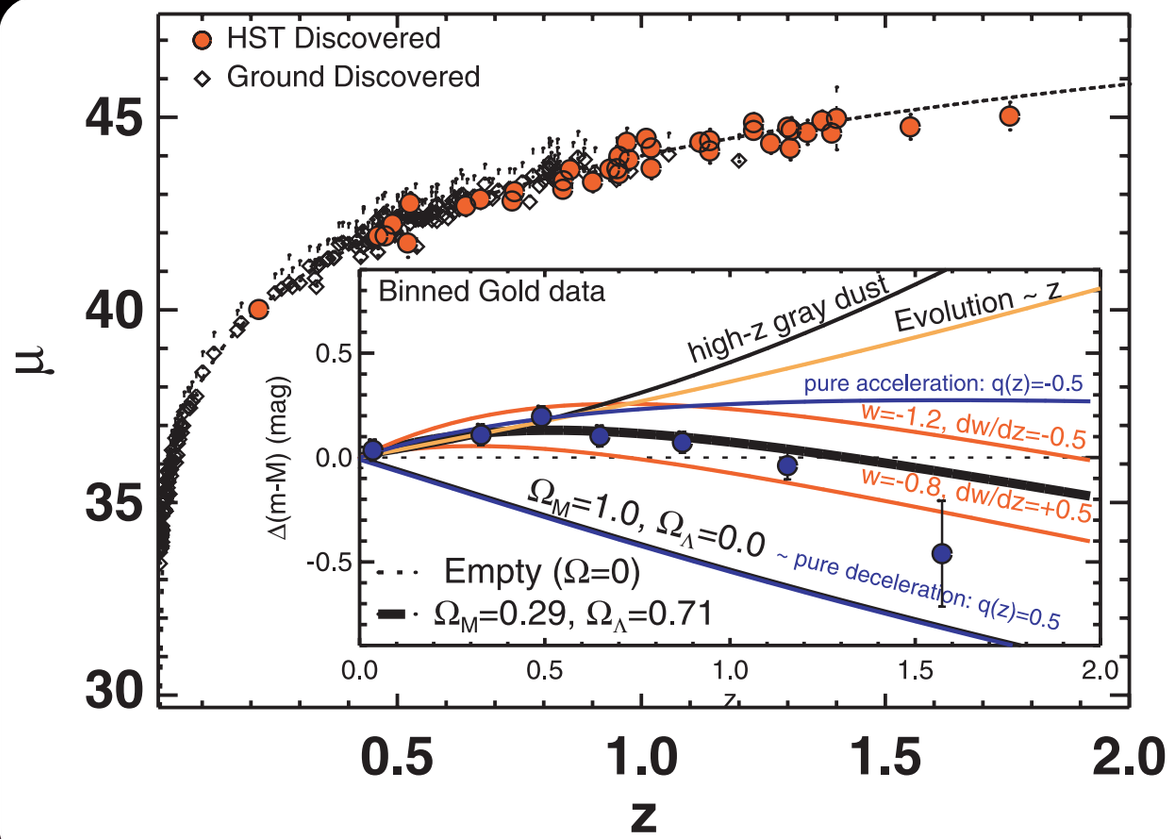
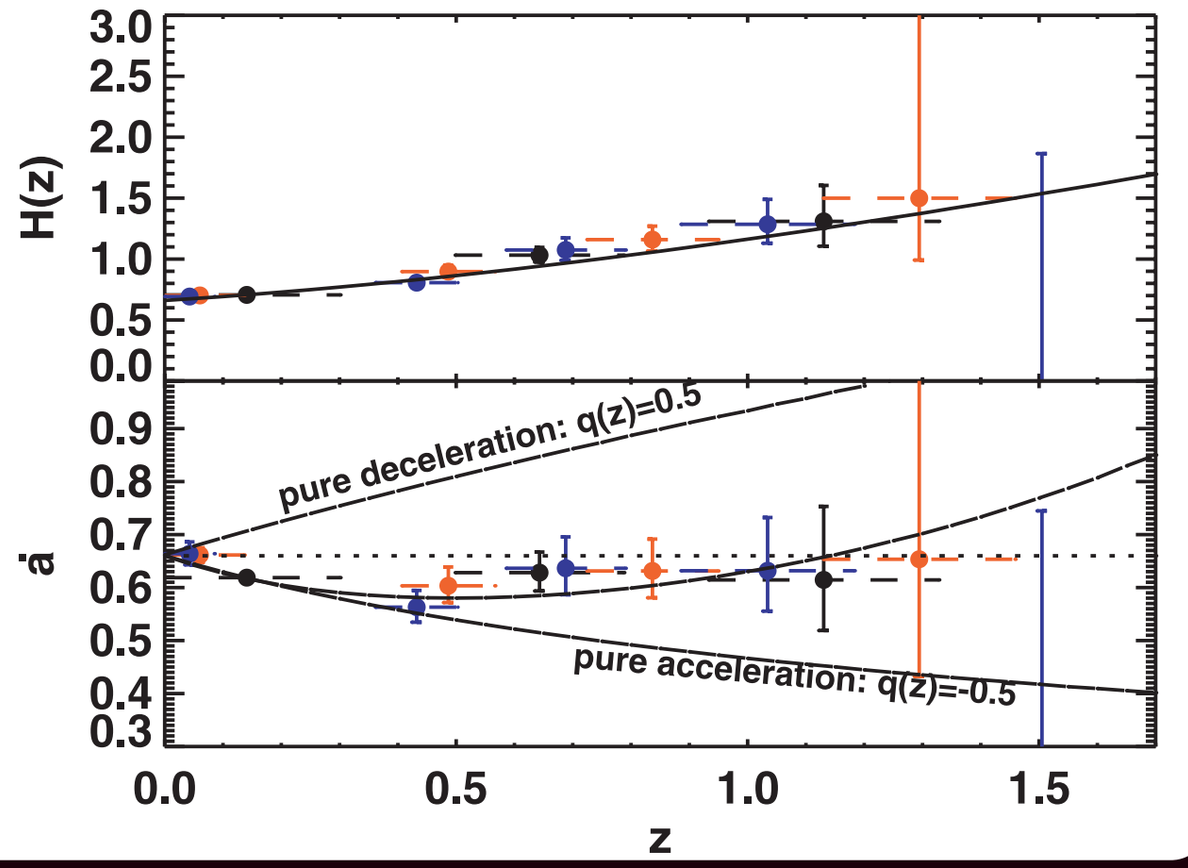
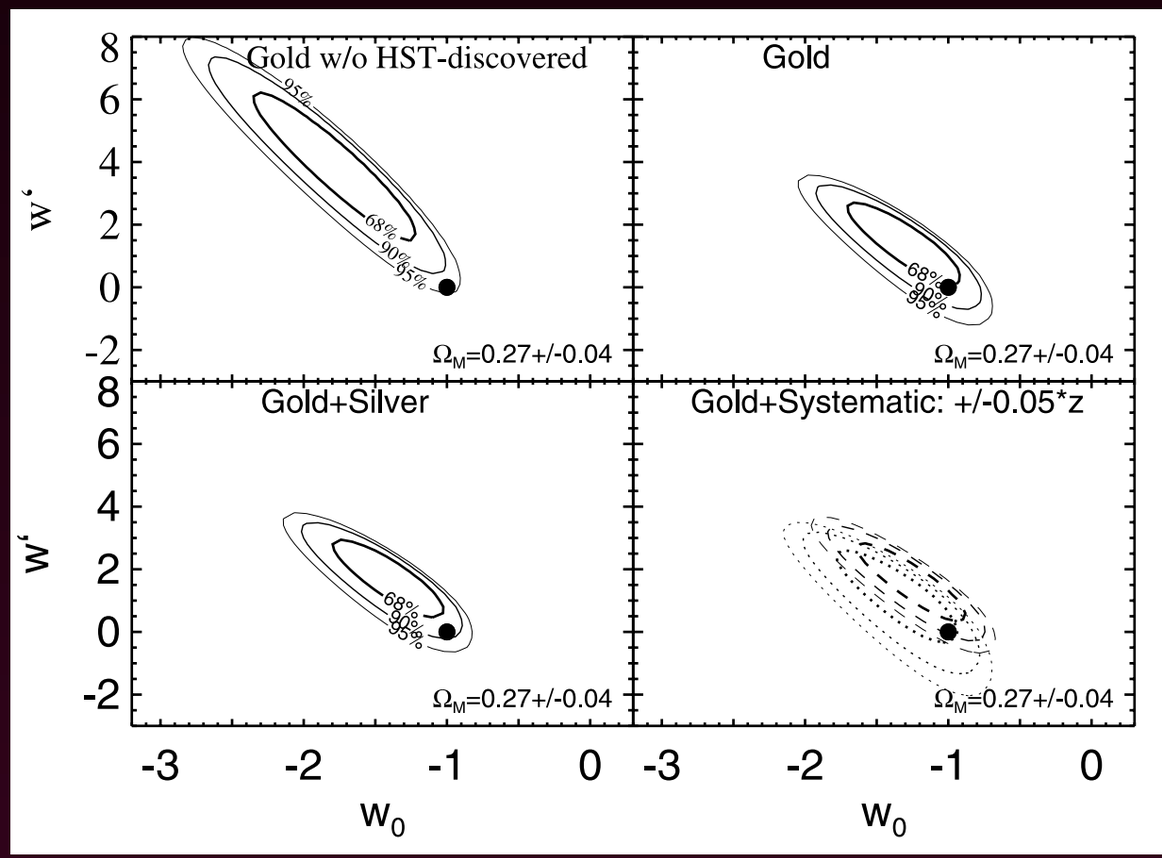




HST-discovered supernovae at very high redshift show the Universe *decelerated* before the current acceleration

they also provide the first constraints on dynamic dark energy, still consistent with the cosmological constant



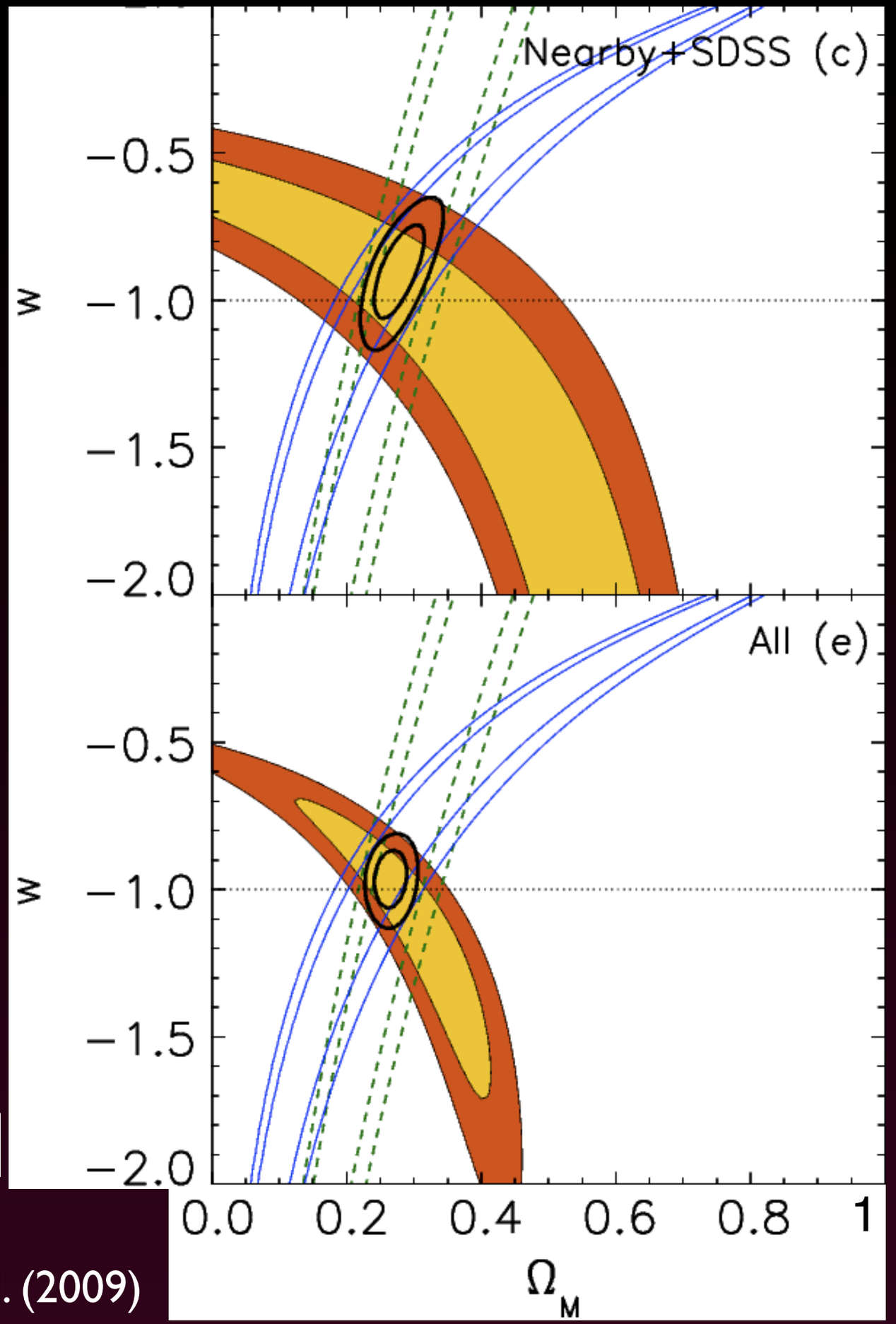
Cosmological results: flat, constant w

with additional constraints from CMB, BAO

Nearby + SDSS

Nearby + SDSS + ESSENCE + SNLS +HST

$$w = -0.96 \pm 0.06(\text{stat}) \pm 0.12(\text{syst})$$



Kessler et al. (2009)

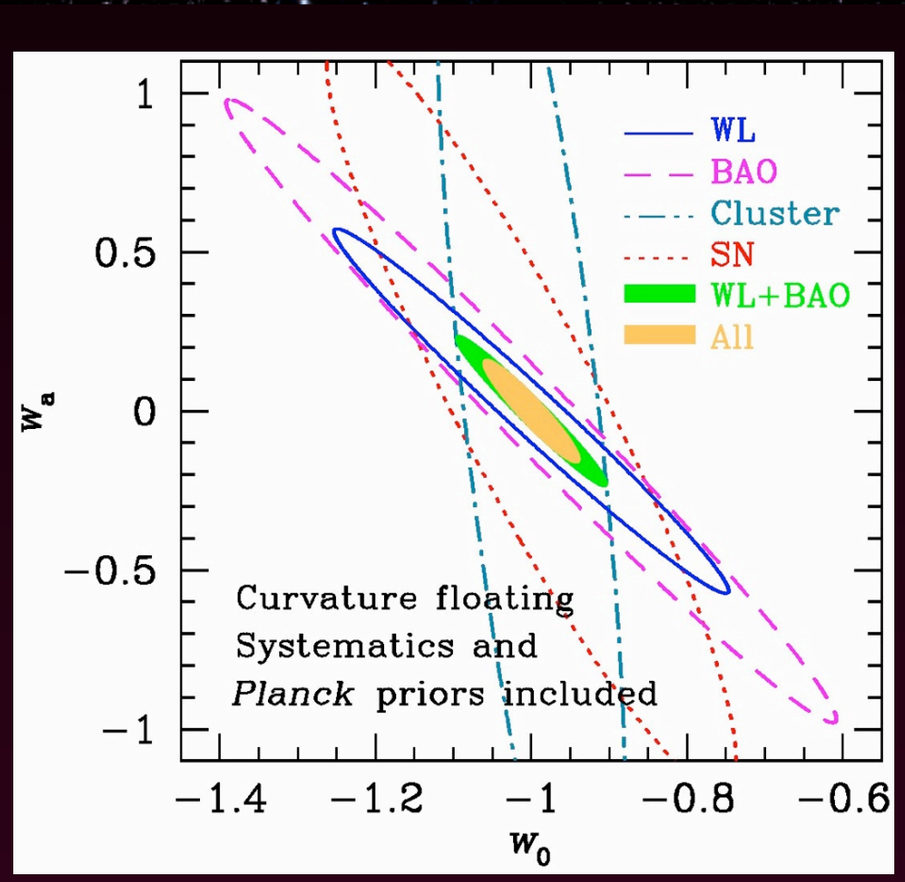
the future of (understanding) dark energy

- cosmology with type Ia supernovae is now *systematics* limited (~10% precision in *w*):
  - progenitors, evolution, standardization, photometric calibration, etc.
  - constraints on *w* to a few percent are still feasible with increasing samples, rest-frame infrared observations

- *complementary techniques* have enormous utility in probing dark energy:
  - cosmic microwave background
  - baryon acoustic oscillation + other LSS
  - local measurement of H_0 (+ with SN Ia)
  - weak lensing
  - galaxy clusters + number counts

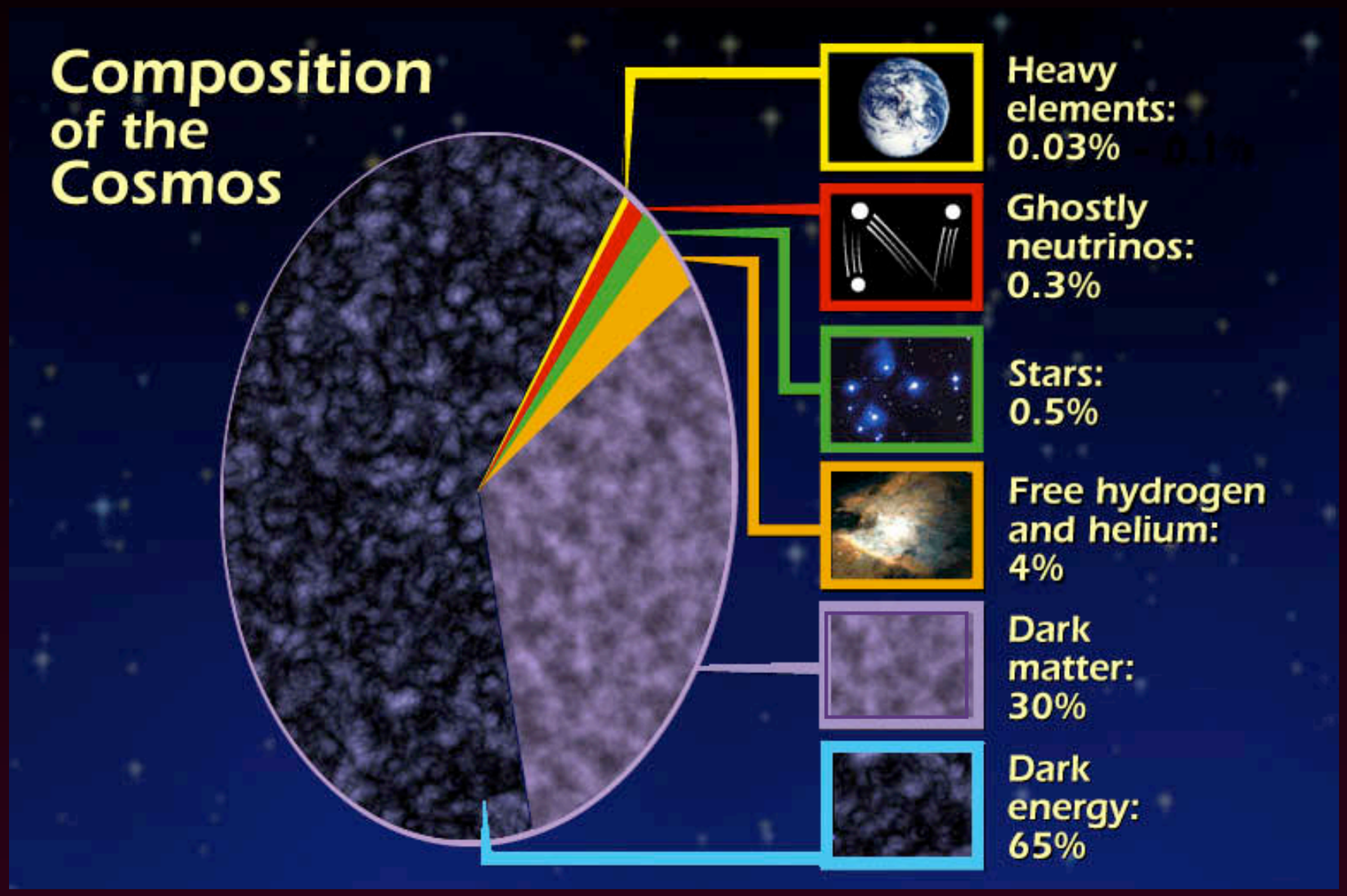
Large Synoptic Survey Telescope

WFIRST
Wide-Field Infrared Survey Telescope



projected dark energy constraints
(figure from lsst.org)

A Preposterous, Extravagant, or Just Interesting Universe?



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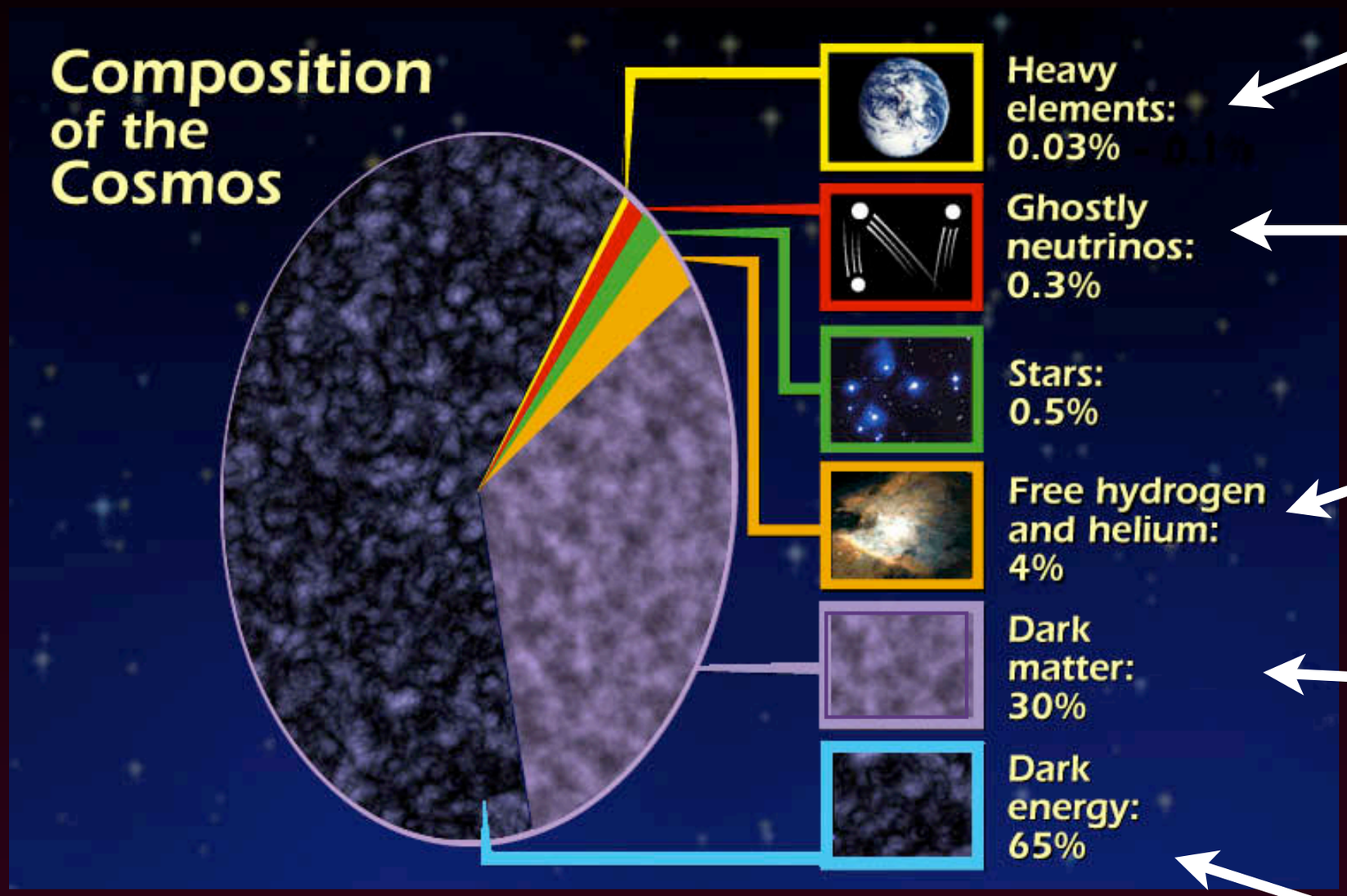

that's us! (ugly bags of mostly water)

ooh, scary!

we're not sure where this is

we don't know what this is

and we know even less about this!